Voice Traffic over Mobile Ad Hoc Networks: A Performance Analysis of the Optimized Link State Routing Protocol

THESIS

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AFIT/GCE/ENG/09-09

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Abstract

This thesis investigates the performance of the Optimized Link State Routing (OLSR) protocol on Voice over Internet Protocol (VoIP) applications in Mobile Ad hoc Networks (MANETs). Using VoIP over MANETs takes advantage of the mobility and versatility of a MANET environment and the flexibility and interoperability a digital voice format affords. Research shows that VoIP-like traffic can be routed through an ad hoc network using the Ad hoc On-demand Distance Vector routing protocol. This research determines the suitability of OLSR as a routing protocol for MANETs running VoIP applications.

Representative VoIP traffic is submitted to a MANET and end-to-end delay and packet loss are observed. Node density, number of data streams and mobility are varied creating a full-factorial experimental design with 18 distinct scenarios. The MANET is simulated in OPNET and VoIP traffic is introduced using one source node to send traffic to random destinations throughout the network.

Simulation results indicate delay is between 0.069 ms to 0.717 ms, which is significantly lower than the recommended 150 ms threshold for VoIP applications. Packet loss is between 0.32% and 9.97%, which is less than the 10% allowable packet loss for acceptable VoIP quality. Thus OLSR is a suitable routing protocol for MANETs running VoIP applications.

Acknowledgements

This document and my journey through AFIT could not have been possible alone, and I want to take a moment to thank those most important to me. First to GOD, whose grace and guidance helped me find my way, especially when I felt so lost. To my mother and her patient ears that listened to my many phone calls of confusion, frustration, aggravation and even the occasional achievement of success. To my friends and colleagues, whose mentoring and humor helped me better myself and know how lucky I am to have been surrounded by such great people. And of course, to Dr. Mullins, who very patiently guided me through the long process that is AFIT and made sure that I never wandered too far from the path to graduation.

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I. Introduction

1.1 Background

A Mobile Ad hoc Network (MANET) poses a challenging environment for Voice over Internet Protocol (VoIP) due to multi-hop routing and dynamic route calculation. Routing in a MANET uses routing protocols such as Ad hoc On-demand Distance Vector (AODV) and Optimized Link State Routing (OLSR). The major difference between these two protocols is AODV is a reactive protocol that searches for new routes as required while OLSR is a proactive protocol that calculates all valid routes whether they are needed or not.

1.2 Problem Definition and Goal

This research determines the suitability of OLSR as a routing protocol for MANETs running a VoIP application. The goal of this research is to determine whether routing protocols affect VoIP end-to-end delay and packet loss in a MANET. The hypothesis is routing protocols have a significant role in VoIP performance in a MANET. Since the route calculation strategies of the two protocols are very different, it is expected OLSR has a larger initial overhead, but reduces individual packet end-to-end delay since valid routes are determined in advance.

1.3 Approach

These research goals are met by sending representative VoIP traffic across a MANET. Objective measurement of delay and packet loss determines whether OLSR provides acceptable performance on the MANET.

The MANET is simulated in OPNET modeler, which is capable of running Discrete Event Simulations (DES). VoIP packets are sent through the network from a source node to random destinations throughout the MANET. End-to-end delay and packet loss results are observed and compared to recommended values for acceptable VoIP quality.

1.4 Implications

This research will be highly beneficial to the United States Air Force for situations were network infrastructure is not available. Examples of these situations include desert battle areas and aircraft flying over a combat zone. Since MANETs are already in use, it may be possible to place VoIP traffic over an existing MANET.

1.5 Summary

The remainder of the document is organized in the following manner: Chapter II provides background research relevant to MANETs and VoIP applications. Chapter III describes the methodology used to study the problem defined in Section 1.2; Chapter IV presents the results and analyzes of the data collected. Chapter V provides conclusions and areas for future work.

II. Literature Review

2.1 Introduction

This chapter provides background material relevant to VoIP and MANETs. Section 2.2 discusses MANETs and their characteristics. Routing protocols used in MANETs are discussed in Section 2.3. Section 2.4 discusses OLSR and its requirements, while Section 2.5 discusses VoIP. An overview of codecs is discussed in Section 2.6, and Section 2.7 provides the related work in this research area. Finally, Section 2.8 summarizes the chapter.

2.2 Mobile Ad Hoc Networks

The major characteristics of an ad hoc network are [MM04]:

- *Mobility*: Mobility can be individual node or group mobility involving random or pre-planned routes. Mobility affects routing and network performance since the network must re-learn node locations after movement.
- *Multi-hopping*: Data can traverse several nodes prior to reaching its destination and must account for obstacle negotiation, spectrum re-use and energy conservation.
- *Self-Organizing*: Ad hoc networks autonomously determine configuration parameters and topology.
- *Energy Conservation*: Nodes rely on limited battery power and usually cannot generate power.
- *Scalability*: As the number of nodes in an ad hoc network increase, the complexity of routing and configuration management also increase.
- *Security*: Ad hoc networks are vulnerable to eavesdropping since transmissions occur in free space.

A MANET is a collection of mobile nodes that communicate without the assistance of a support infrastructure [Ahm05]. This characteristic is desirable in various

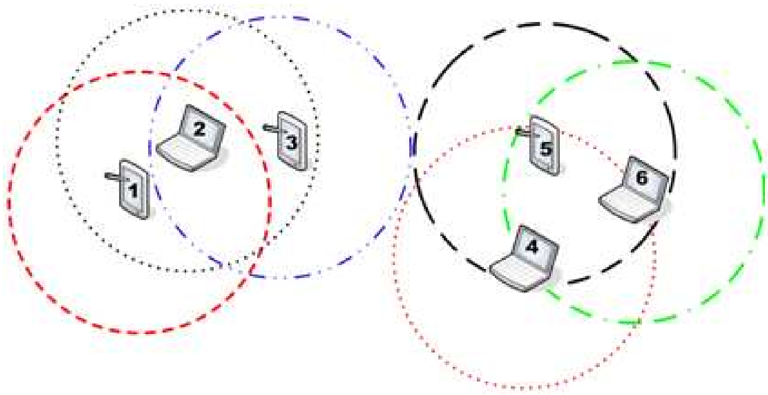


Figure 2.1: Ad Hoc Network with Six Nodes [Ahm05]

situations such as during natural disasters and in military environments where deploying an infrastructure can be expensive or infeasible.

Figure 2.1 shows an ad hoc network with six nodes outfitted with omni-directional antennas. Each node can send and receive data within its transmission range (each node is centered in its transmission range circle). If more than one node is in a circle, then communication can occur between the encircled nodes. Node 1 can communicate with node 2 since they are in the same circle (i.e., their transmission ranges overlap). Node 3, however, can only communicate with node 1 only if node 2 forwards the packets.

Since none of the transmission ranges of nodes 1, 2, or 3 overlap with any of the transmission ranges of nodes 4, 5, or 6, there is no way for nodes 1, 2, or 3 to communicate with nodes 4, 5, or 6 [Ahm05].

The MANET working group, created within the Internet Engineering Task Force (IETF), exists due to the necessity for open standards regarding MANETs [Ily03]. The MANET working group standardizes Internet Protocol (IP) routing protocols and provide functionality with an emphasis on wireless routing - accounting for both static and dynamic topologies [MK04]. The standards developed by the MANET working group are intended to handle networks employing various hardware with wired and wireless hosts. This includes infrastructures with fixed and mobile router implementations.

The Request for Comments (RFC) the MANET working group has established include MANET: Routing Protocol Performance Issues and Evaluation Considerations (RFC 2501), AODV Routing Protocol (RFC 3561) and OLSR Protocol (RFC 3626) [IET03].

2.3 Ad Hoc Routing Protocols

Routing in an ad hoc network is different than routing in an infrastructure-based network, because ad hoc networks have characteristics not found in infrastructure-based networks such as multi-hop routing. A routing protocol can be evaluated using the following metrics [Ahm05]:

- *End-to-end Data Throughput and Delay*: Throughput and delay are measured from the perspective of applications that use the routing. Throughput and delay measure a routing policy's effectiveness and are important when dealing with Constant Bit Rate (CBR) applications such as real-time audio or video.
- *Route Acquisition Time*: This is the time required to establish route(s) when requested and is affected by the type of routing protocol.
- *Efficiency*: This is the internal measure of the routing protocol's effectiveness and can be measured as either overhead or throughput versus input traffic.

Figure 2.2 shows the routing protocols for ad hoc networks. The routing protocols for MANETs can be classified into three main types - proactive, reactive, and hybrid [Ahm05]. Table 2.1 compares the three types of MANET routing protocols classified as flat routing in Figure 2.2.

Proactive, or table-driven routing protocols, maintain valid routes from each node to every other node in the network by establishing routes before data packets are sent across the network. Periodic updates are flooded throughout the network to report link and topology changes. The OLSR protocol, which is discussed in Section 2.4, is such a protocol.

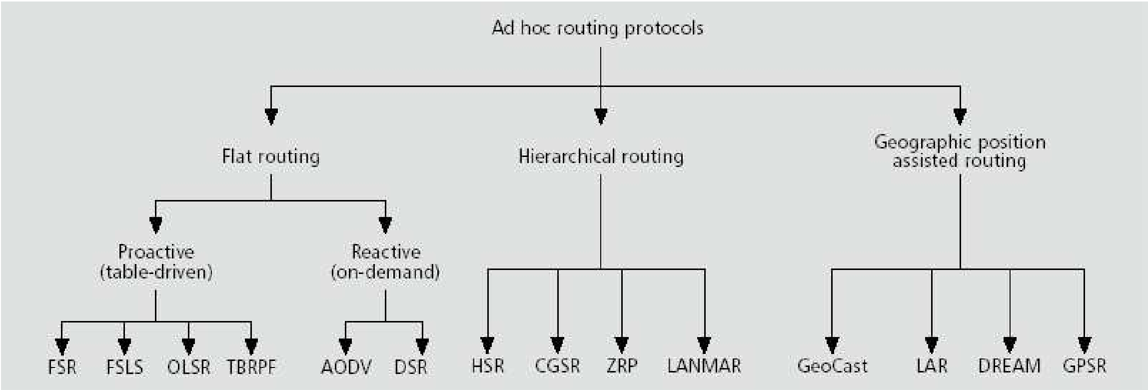


Figure 2.2: Classification of Ad Hoc Routing Protocols

Table 2.1: Types of Ad Hoc Routing Protocols [Ahm05]

	Proactive	**Reactive**	**Hybrid**
Routing Structure	Can be flat or hierarchical	Mostly flat	Mostly hierarchical
Route Availability	Always available	On-demand	Depends on location of destination
Volume of Control Traffic	High	Lower than proactive	Lowest
Periodic Updates	Yes	Not required	Yes, within a zone or cluster or between gateways
Delay	Low	High	Depends on location of destination

Reactive, or on-demand routing protocols, establish routes only as needed. This increases end-to-end delay compared to proactive routing protocols since routes are calculated when data packets are ready to be sent. However, periodic updates are not required as in proactive routing. Ad hoc On-Demand Distance Vector (AODV) is a reactive routing protocol.

Hybrid routing protocols take advantage of the benefits from both proactive and reactive routing types. A proactive protocol (i.e., OLSR) is used for destination nodes within a certain number of hops from the source. Any destination outside of this region uses the reactive protocol (i.e., AODV).

2.4 Optimized Link State Routing Protocol

OLSR, first presented by Philippe Jacquet, Paul Muhlethaler, Thomas Clausen, Anis Laouiti, Amir Qayyum and Laurent Viennot in 1998 [JMQ98], concentrates on routing in ad hoc networks [JMC+01]. It is a proactive routing protocol based on the link state algorithm and provides the following optimizations to the classic link state algorithm - it reduces the size of control packets by implementing Multipoint Relays (MPRs), only declares a subset of links with neighbors that are its multipoint relay selectors instead of all nodes, minimizes flooding of control traffic by only permitting select nodes, MPRs, to send control traffic through the network, and does not generate extra control traffic in response to link failures or arriving nodes [CJ03].

OLSR does not require reliable transmission of control traffic since control messages are sent periodically. It is, therefore, able to sustain control message losses without severely impacting performance. Since each control message contains a sequence number that is incremented only when a new periodic message is sent, OLSR tolerates out-of-order delivery [JMC+01].

2.4.1 Multipoint Relays. MPRs are a subset of all the one-hop neighbors of a node chosen in such a way that all two-hop neighbors are covered by this set. These nodes are the only nodes that forward broadcast messages during the flooding

process. This reduces overhead since in a classical flooding mechanism, every node retransmits each message it receives the first time. The goal of MPRs is to minimize control message traffic sent throughout the network, thereby reducing overhead and conserving battery life. An OLSR route in an ad hoc network is a sequence of hops through the MPRs from source to destination [JMC+01].

Figure 2.3 compares MPR flooding to full flooding as used by classic flooding mechanisms. In full flooding, all nodes receive control messages and retransmit (or flood) the message to all its neighbors. Thus, a node may receive the same message from multiple neighbors. In MPR flooding, only the MPR nodes retransmit the message to their neighbors. All other nodes process the message but do not retransmit. All nodes still receive the message through MPR flooding, but with less overhead as compared to full flooding.

Each node in the network selects a set of nodes among its neighbors to retransmit its packets. This set contains the MPRs for that node. Thus, a smaller MPR set results in an optimal OLSR. Nodes chosen as MPRs maintain an MPR selector set. This set lists all the nodes that have chosen it as an MPR [JMC+01].

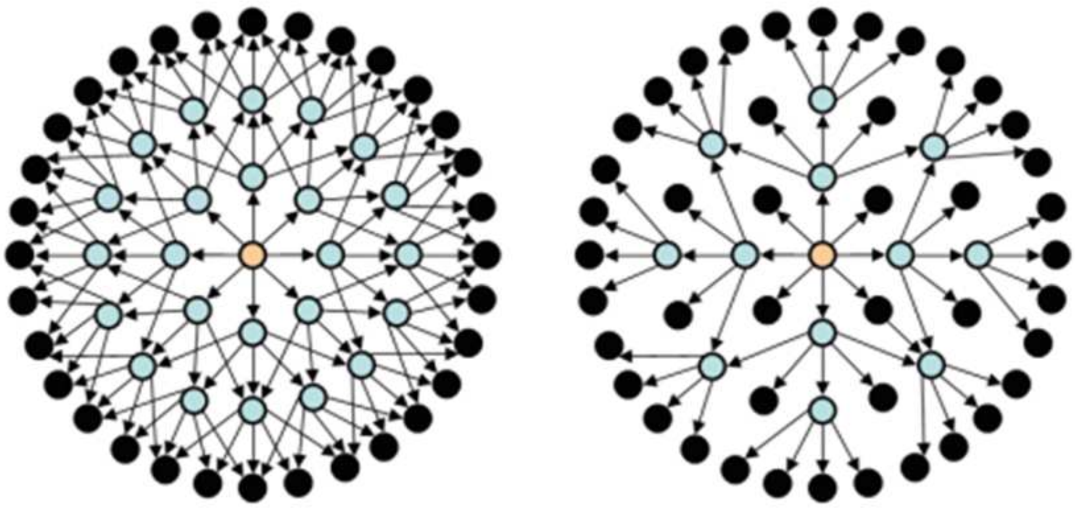


Figure 2.3: Comparison of Full Flooding (left) and MPR Flooding (right) [UNI06]

Figure 2.4 shows a MANET with direct links depicted by the lines between the nodes. All one-hop neighbors of X are shown by the inner circle and all two-hop neighbors of X are shown by the outer circle. Figure 2.5 shows the MPR set of X containing nodes A, B, C and D. By selecting these nodes, all two-hop neighbors of X are covered [JMC+01]. Even though node E is a one-hop neighbor of X, its two-hop neighbors are covered by other nodes already in the MPR set - nodes A and D. Therefore, node E is not included in the MPR set.

2.4.2 HELLO Messages. Nodes learn about their neighbors through HELLO messages. HELLO messages are broadcast by each node in the network and perform the following tasks [JMC+01]:

- *Link Sensing* contains the links associated with the node using the local link set. The local link set lists all nodes that have a link with the node of interest as well as their link status. A link's status can be bi-directional, unidirectional, or MPR.
- *Neighbor Detection* declares all the neighbors of the node using the neighbor set. The neighbor set lists all the neighbors of the node of interest, up to two hops away.
- *MPR Selection Signaling* declares the MPRs of a node using the MPR set. The MPR set lists all the nodes that the node of interest has chosen as its MPRs.

HELLO messages are generated and broadcast periodically based on changes to the local link set, neighbor set and MPR set [JMC+01].

2.4.3 Topology Control Messages. Each node periodically broadcasts Topology Control (TC) messages to declare its MPR selector set and populate its topology table. These messages are forwarded like usual broadcast messages throughout the entire network (through MPRs) and are sent at normal intervals unless there has been a change to the MPR selector set. A change to the MPR selector set results in a TC

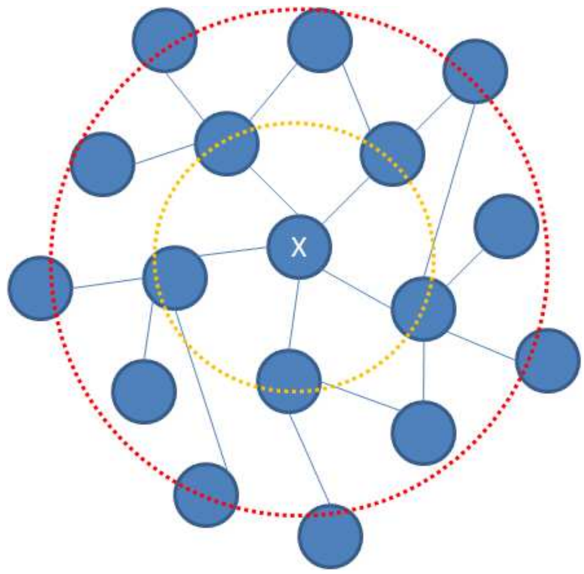


Figure 2.4: A MANET Showing One and Two-Hop Neighbors of Node X

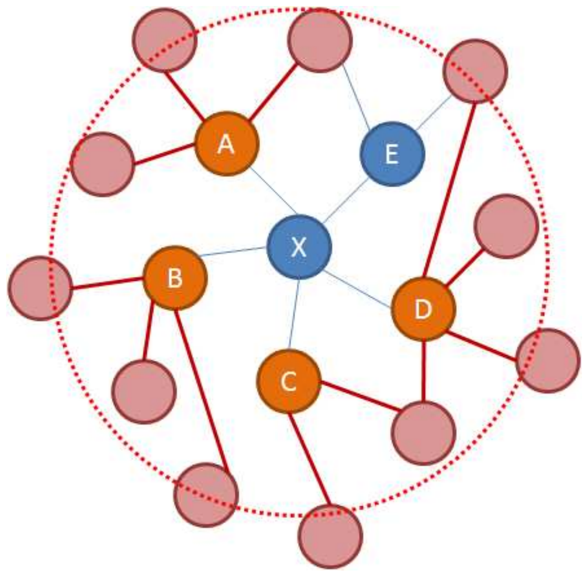


Figure 2.5: MANET with MPR Set of X Containing Nodes A, B, C and D

message sent sooner than the interval. A node with an empty MPR selector set (i.e., nobody has selected it as an MPR) does not generate TC messages [JMC+01].

The topology table, maintained at each node, records information about the topology of the network as obtained from TC messages. This topology information is used to calculate routes for the routing table. Each topology table entry has an associated holding time; once expired, the entry is marked invalid and is removed [JMC+01]. The topology table maintains topology information by recording [JMC+01]:

- *Destination Addresses*: These are the MPR selectors obtained from the TC message. These nodes selected the node of interest as an MPR and are the nodes that the node of interest must forward messages to.
- *Destination's MPR*: These are the last-hop node to the destination. These nodes are the originators of the TC messages and provide the route to the MPR selectors.
- *MPR Selector Sequence Number*: This sequence number is maintained to specify the most recent MPR selector set. It is only incremented when the MPR selector set has been modified.
- *Holding Time*: This specifies how long an entry will be maintained in the topology table.

2.4.4 Route Table Calculation. A routing table is kept at each node and contains routes to all other destinations in the network. This table is built by tracking connected pairs (i.e., pairs whose link status is bi-directional) in the topology table. In order to obtain optimal paths, only connected pairs are selected on the minimal path. There is no entry for destinations whose routes are broken or are not fully known. Route table entries contain the destination address, next-hop address, and estimated distance to destination (in number of hops) [JMC+01]. Figure 2.6 shows a routing table for Node X in the MANET. Topology table entries not used to calculate the routing table are discarded, and the routing table is re-calculated if there are

Dest	Next-hop	Distance
A	A	1
B	B	1
C	C	1
D	D	1
E	E	1
O	A	2
N	A	2
M	B	2
L	B	2
...	...	...

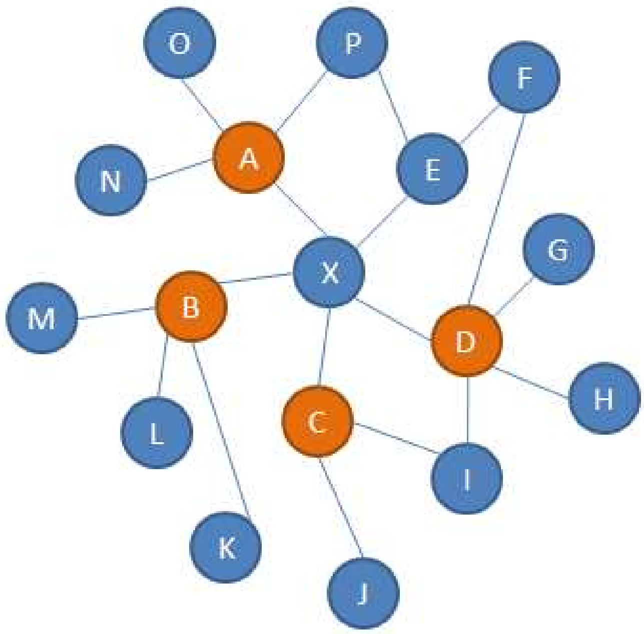


Figure 2.6: Routing Table (left) for Node X in the MANET (right)

changes to either the neighbor table or the topology table. It is also re-calculated if routes have expired or if there have been updates to bi-directional links.

2.5 Voice over Internet Protocol

VoIP is a relatively new technology that sends digital voice data over packet switched networks. Conventional voice telephony is transported in full duplex mode on Public Switched Telephone Network (PSTN) circuits optimized for voice [VSMH02]. In VoIP, analog voice data is converted to a digital format and compressed using a coder/decoder (codec). This stream of binary data is then sent to the Transmission Control Protocol (TCP)/IP stack where it is broken into a series of packets for transmission across the network [Wal05]. Once at the receiver, the IP packets are stripped of their headers and the payload is sent as a constant bit stream to a compatible codec [HPG05].

Figure 2.7 shows how the VoIP packet is divided into the payload and headers. The headers associated with the VoIP packet are the Internet Protocol version 4

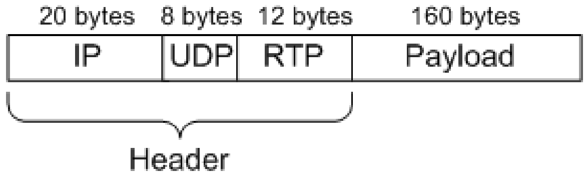


Figure 2.7: VoIP Packet

(IPv4) header, the User Datagram Protocol (UDP) header, and the Real-time Transport Protocol (RTP) header [Wal06].

2.6 Codecs

A codec digitally encodes an analog voice signal. The objective of a codec is to obtain the lowest rate bit stream possible after conversion without degrading the quality of the signal such that the received audio signal can be generated without noticeable differences in quality [MM04].

Table 2.2 describes various codecs used on packet networks. The bit rate depends on the codec used and is the number of bits per second required to deliver a voice call. The sample size is the number of bytes captured from the analog signal during the sample interval. Packets Per Second (PPS) represents the number of packets that must be transmitted in order to maintain the codec bit rate. The payload size is the bytes that fill the packet. Depending on the codec and the header size required for coding, packets can have various payload sizes. However, the payload size must be

Table 2.2: Speech Codecs Used in Packet Networks [ITU88]

Codec	**Bit rate** (kbps)	**Sample size** (bytes)	**Packets per second**	**Payload size** (bytes)
G.711 8-bit PCM	64	80	50	160
G.723.1	6.3	24	34	24
G.723.1	5.3	20	34	20
G.726	32	20	50	80
G.728	16	10	50	60
G.729a	8	10	50	20

a multiple of the sample size [FS06]. This study concentrates on the specifications of the G.711 codec, which is commonly used for real-time audio applications like VoIP. G.711 is an 8-bit Pulse Code Modulation (PCM) codec. It samples 80 bytes every 10 ms resulting in a 160 byte payload for a VoIP packet [ITU88].

2.7 Related Work

2.7.1 OSPF versus OLSR. Link state routing algorithms induce overhead to route traffic in wireless ad hoc networks. Adjih et al. examines the overhead due to link state routing in an ad hoc network. Specifically, they study the classic link state protocol Open Shortest Path First (OSPF) and OLSR. In addition, they study how link state routing overhead evolves when node density increases [ABJ03].

The major difference between OSPF and OLSR is the source of control traffic. OLSR uses neighbor sensing and periodically sends HELLO messages containing a list of its neighbors. In contrast, OSPF uses topology discovery where each node sends a list of its adjacent links in a Link State Advertisement (LSA). Neighbor nodes re-broadcast this LSA to their neighbors.

Adjih et al. shows the specific routing algorithm used impacts the maximum manageable neighbor size for both OSPF and OLSR. The overhead due to the routing protocol increases as the neighborhood size increases. Thus, OSPF can have a manageable neighborhood size of 12 nodes, while OLSR can manage a neighborhood of 50 nodes. Overall, OSPF performs poorly when compared to OLSR [ABJ03].

2.7.2 VoIP Traffic in Multi-Hop Ad Hoc Networks. Multi-hop environments such as MANETs create situations not normally seen in wired networks. Armenia et al. study real-time audio traffic on multi-hop IEEE 802.11b ad hoc wireless networks via simulations and a testbed including both proactive and reactive routing protocols, specifically OLSR and AODV. Figure 2.8 shows the testbed topology, and Table 2.3 lists the specific configurations of the hosts. The testbed consists of four stationary hosts and a 30 second audio file sampled at 8 kHz and 8-bit encoding. This VoIP file

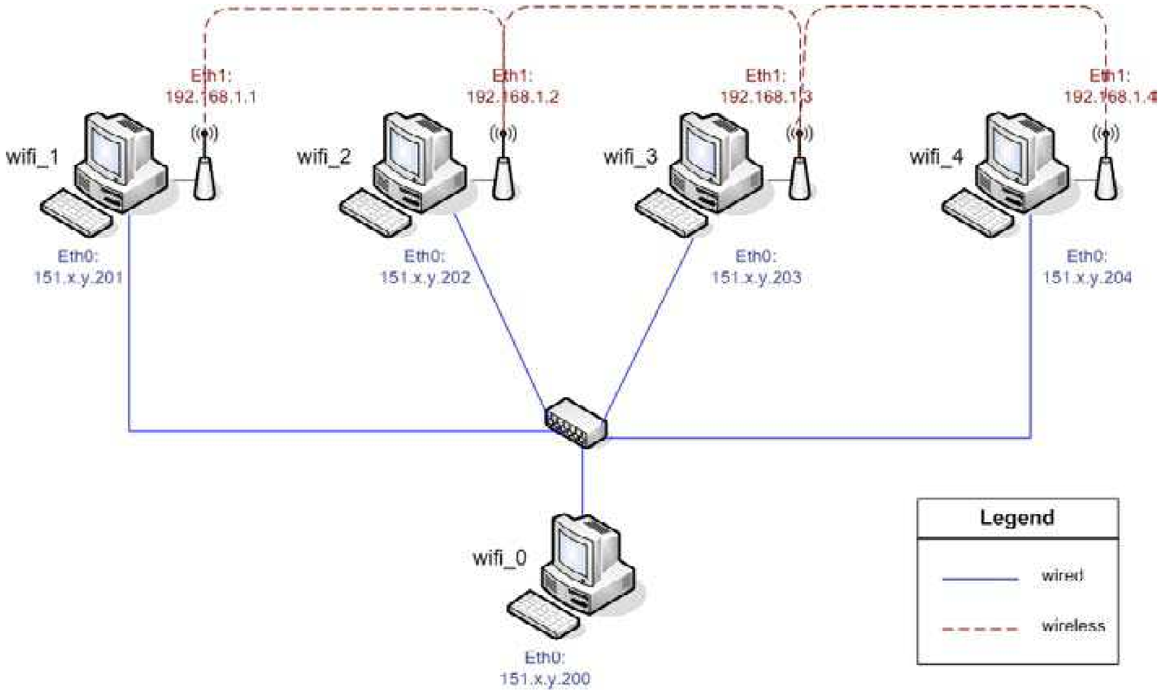


Figure 2.8: Testbed Topology [AGLP05]

is sent using the GnomeMeeting tool and subsequently analyzed at the receiver using Ethereal [AGLP05].

The codec does not affect the routing protocol performance nor is there a noticeable difference between OLSR and AODV throughput and delay jitter. However, varying the number of hops results in a noticeable difference between OLSR and AODV end-to-end delay. For all codecs studied, AODV returns an end-to-end de-

Table 2.3: Testbed Host Configurations [AGLP05]

CPU	AMD Duron 1.6 GHz, 64 KB cache Intel Pentium III 800 MHz, 256 KB cache
RAM	256 MB 128 MB
PCI Fast Ethernet Card	VIA Rhine II Fast Ethernet Adapter
Wireless PCI card	802.11b ADMtek

lay averaging 0.07 seconds higher than OLSR [AGLP05]. These results are only for stationary hosts in an 802.11b ad hoc network. Mobile hosts have different results.

2.7.3 Investigating MANETs in a VoIP Context. Prior research has investigated the performance of MANETS carrying VoIP traffic. Thibodeau et al. studied whether MANETs offer a suitable platform for VoIP networks by determining one-way delay and jitter. They implement a MANET with AODV as the routing protocol using Network Simulator 2 (ns-2). Their research concentrates on three factors [TYH06]:

1. *Node Density*: The number of nodes in the network varies between 30 and 90 for a fixed simulation surface of 1,000 m by 1,000 m. A fixed number of data streams (five) is used.
2. *Number of Data Streams*: The number of streams sent through the network is between 5 and 25 with a fixed node density of 50 nodes in a 1,000 m by 1,000 m area.
3. *Route Length*: They observe the relation between route length and interruption duration. Using a fixed area of 1,600 m by 1,600 m with 128 nodes and 10 data streams, the number of hops contained in the repaired route is observed.

Thibodeau et al. concludes that node mobility and node density have limited influence on the performance of the routing protocol. However, route length and network load (number of data streams) prove to be critical factors in the performance of AODV. They found that Medium Access Control (MAC) layer misbehavior causes more than 80% of route losses. This misbehavior is attributed to the 802.11 MAC layer returning an error to the routing protocol. These errors are caused by MAC layer unfairness and hidden and exposed terminal problems. Aside from MAC layer misbehavior, the routing protocol is responsible for high interruption durations. When a link loss is detected by AODV, it must re-calculate the route. This re-calculation requires too much time to provide VoIP users acceptable quality [TYH06]. These

results are only valid for MANETs running AODV. Running a MANET with OLSR could minimize the re-calculation time.

2.8 Summary

MANET routing protocol research compares OSPF and OLSR. Adjih et al. concluded that OSPF performs poorly when compared to OLSR. OLSR is also able to manage neighborhoods up to 50 nodes. This study uses OLSR as the routing protocol and studies networks of a maximum size of 50 nodes.

Current research in VoIP and MANETs involve both simulations and testbeds. Most studies account for mobile nodes and study the routing protocols AODV and OLSR. For example, Thibodeau et al. study the effects of AODV on MANETs. However, they do not study the effects of using other routing protocols such as OLSR. Since numerous benefits can be realized by using different routing protocols in this environment, this study determines whether OLSR can successfully route VoIP packets in a MANET.

Armenia et al. only study stationary hosts in IEEE 802.11b ad hoc wireless networks. Without accounting for mobility, different results for OLSR can be experienced since mobile nodes would require route re-calculation, and could actually return comparable end-to-end delay as AODV.

However, this study looks at both static and mobile environments in an IEEE 802.11g MANET in the effort to observe OLSR performance.

III. Methodology

3.1 Introduction

This chapter discusses the methodology for this research. Section 3.2 discusses system boundaries, including the component under test. The system services are described in Section 3.3, and Section 3.4 provides an overview of the workload presented to the system. Section 3.5 discusses performance metrics, and Section 3.6 discusses system parameters. Workload parameters are discussed in Section 3.7, while Section 3.8 details the factors chosen for the experiment. Section 3.9 explains the evaluation technique, and Section 3.10 describes the experimental design. Finally, Section 3.11 summarizes the chapter.

3.2 System Boundaries

The System Under Test (SUT) is the VoIP MANET (VoMAN) System. Figure 3.1 shows the components of the SUT. The VoMAN system consists of four major components - ad hoc nodes, an ad hoc network, routing protocol, and the IEEE 802.11 MAC layer protocol.

3.2.1 Ad Hoc Nodes. Each node in the ad hoc network functions as both a client and a server. As clients, the nodes complete two tasks - send requests to the network and receive information from the network. As servers, the nodes process information received from the network and determine whether packets require forwarding. If so, the node services the packet accordingly. Thus, each node provides the services of both a router and an end unit.

3.2.2 Ad Hoc Network. The ad hoc network is measured by observing VoIP traffic as it travels through the network. This network provides the medium that transports VoIP traffic from one ad hoc node to another. This network is simulated in OPNET using the wireless network suite.

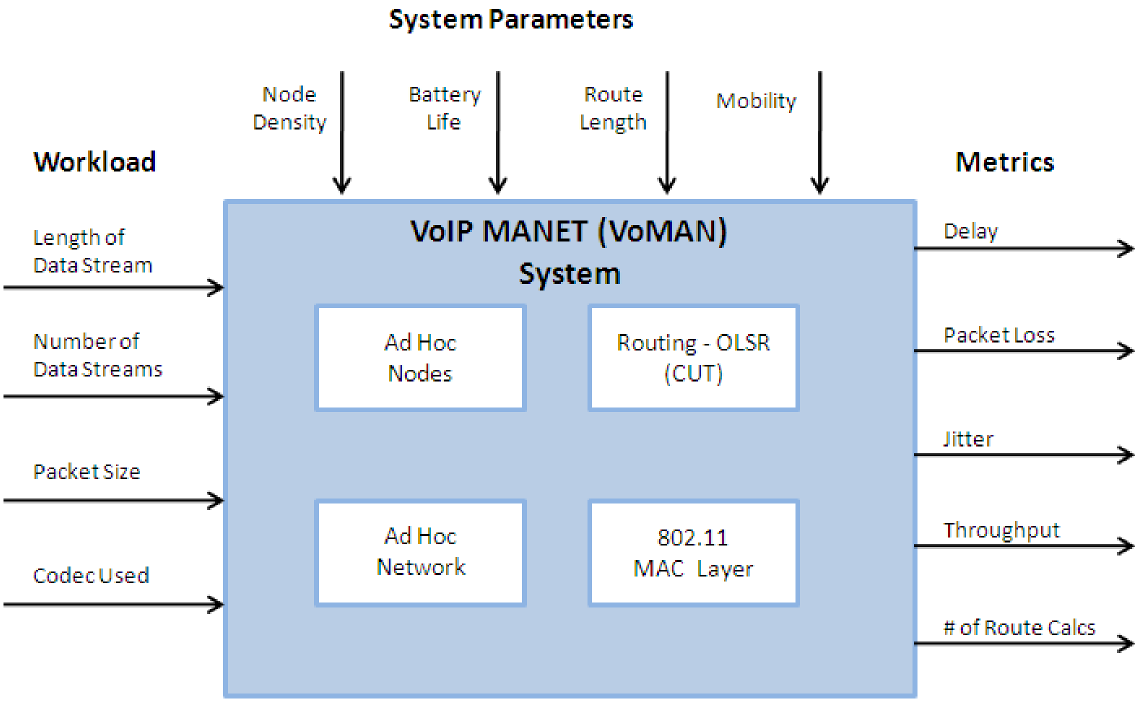


Figure 3.1: The VoIP MANET (VoMAN) System (SUT).

3.2.3 Routing Protocol - OLSR (CUT). When there are no direct links between the sender and receiver, packets must pass through other nodes in the network to reach their destination. This multi-hop routing is implemented using routing protocols. OLSR is the Component Under Test (CUT). OLSR determines routes from each node to every other node in the network. Section 2.4 details the specifications of OLSR.

3.2.4 MAC Layer Protocol - IEEE 802.11g. A MAC layer protocol provides coordinated access to the network. Table 3.1 contains the specifications of the 802.11g protocol used for this study. The MAC layer is responsible for the transport of frames at the data link layer.

Table 3.1: Specifications of IEEE 802.11g MAC Layer Protocol [IEE03]

Maximum data rate	54 Mbps
Modulation	Complimentary Code Keying (CCK) / Orthogonal Frequency Division Multiplexing (OFDM)
Data rates (Mbps)	CCK: 1, 2, 5.5, 11 OFDM: 6, 9, 12, 18, 24, 36, 48, 54
Frequencies (GHz)	2.4–2.497

3.3 System Services

The service VoMAN provides is VoIP calls over a MANET. The system accepts VoIP data streams as input and transports the streams to the appropriate destination. Figure 3.2 shows the possible outcomes of the VoMAN system which are:

- The call is received with no errors and no re-routing is required.
- The call is received, but a new route is required resulting two possible outcomes:
  - A valid route is found.
  - A valid route is not found and the call is dropped.
- The call is dropped prior to being received because:
  - No valid route is found.
  - The call is dropped due to some other network error.

Since the CUT is the routing protocol, it is assumed the call is specified correctly by the sender and the receiver receives the call under normal conditions. That is, both the sender and receiver having compatible hardware and software and are able to communicate with each other (i.e., they are both part of the same MANET). This excludes cases where calls are dropped due to application error and user error.

This experiment determines whether the routing protocol can obtain valid routes. Therefore, the outcomes considered are calls received when - no re-routing is required and re-routing required and a new valid route is calculated (all other outcomes are excluded).

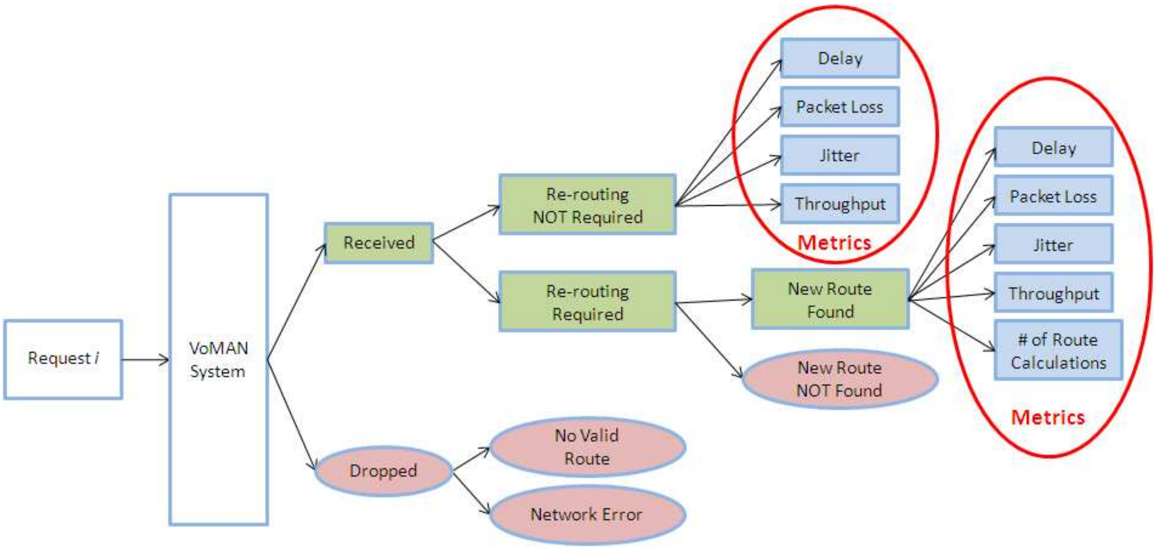


Figure 3.2: Possible Outcomes of the VoMAN System

3.4 Workload

To analyze the performance of the MANET with VoIP traffic, it is crucial to properly simulate representative VoIP streams. As shown in Figure 2.7, each VoIP packet includes 160 bytes of payload and 40 bytes of header. The resulting VoIP packet size using the G.711 codec is 200 bytes. Packets originate from the same source node and are transmitted to random destinations throughout the network. Packets are generated and sent consecutively during the simulation period beginning at 0.0 seconds. The length of the simulation period is 1 day to allow the system to reach and maintain a steady state. The random waypoint model requires a warm-up period of approximately 20,000 seconds [VOKS07].

3.5 Performance Metrics

Performance metrics are used to establish the performance of systems. The performance metrics (circled in Figure 3.2) are delay, packet loss, jitter, throughput, and number of route calculations.

Evaluating performance in a MANET for VoIP traffic requires end-to-end delay and packet loss be minimized since VoIP applications are sensitive to any type of

latency and packet loss. These metrics are compared to the recommended values for each to determine whether OLSR can support VoIP traffic in a MANET.

3.5.1 End-to-End Delay. Delay is measured from the instant a packet leaves the sender's Network Interface Card (NIC) to the instant it is received at the destination's NIC. According to the International Telecommunications Union (ITU) Recommendation G.114, delay in VoIP applications should never exceed 400 ms otherwise the quality of the VoIP stream is significantly degraded. However, the average delay for a VoIP stream should be less than 150 ms for acceptable perceived quality [ITU03]. This end-to-end delay includes any time needed to calculate a new route and other routing delays such as router (i.e., another ad hoc node) processing and queuing delays.

3.5.2 Packet Loss. VoIP applications are sensitive to packet loss. Even though VoIP applications tolerate packet loss up to 10%, a packet loss of 1% still affects the quality of the VoIP stream [ITU03]. Packet loss is measured as the percent of packets dropped at the receiver prior to data stream playback.

3.5.3 Jitter. When referring to VoIP applications, jitter occurs when packets are received with variances in delay. Packets can arrive out-of-order due to these delay variances or because of routing (i.e., a packet travels a different route than a prior packet). Variances in delay are due to packet position in queues along the path from source to destination. One packet could experience minimal queuing delays while the packet sent after it experiences long queuing delays along the same path. This affects the quality of streaming audio like VoIP [HPG05]. Jitter buffers at the receiver temporarily store packets to mask the variances in delay. Jitter, in this study, is measured at the receiver and does not assume any jitter buffers.

3.5.4 Throughput. Throughput is the total number of bits that are sent through the channel per second. The channel is the ad hoc network, thus, throughput

is the maximum number of bits that can be sent per second through the ad hoc network.

3.5.5 Number of Route Calculations. When a new route is required, OLSR re-calculates the route because the current route is no longer valid. This is the number of times OLSR recalculates the routing table for a given stream.

3.6 System Parameters

The system parameters that affect the performance of the VoMAN system include number of nodes in a given area (node density), battery life, number of hops (route length), and mobility.

3.6.1 Node Density. Node density is the number of nodes in the simulation area. It is considered since OLSR should perform better in a denser network. Hence, it is assumed that as the number of nodes in a fixed area increase, the performance of OLSR improves. Section 3.8 discusses node density as a factor for this study.

3.6.2 Battery Life. Battery life is an important issue in MANETs. Since nodes are not always connected to power, batteries must have long life or include a mechanism that conserves energy while performing network tasks. Battery life is not set for this experiment since no battery attribute exists in OPNET for the node model. Therefore, the same battery life is assumed.

3.6.3 Route Length. If the sender and receiver are linked directly, then route length has minimal impact. However, if the sender and receiver do not have a direct link and the packets require routing through multiple hops, then route length plays a major role in the MANET. Increased delay, jitter, and packet loss could result from a long route length. Route length is not observed in this study. Route length is determined by the routes calculated by OLSR in OPNET.

3.6.4 Mobility. Static nodes in a MANET are not representative of real-world situations. Nodes in MANETs do not remain stationary for extended periods of time. Two levels of mobility are considered: all nodes are mobile or all nodes are static. Section 3.8 discusses mobility as a factor for this study.

3.7 Workload Parameters

Workload parameters that affect performance on the VoMAN system include the length of the VoIP data stream, number of data streams, packet size, and codec used.

3.7.1 Length of Data Stream. The number of packets in a VoIP data stream depends on the length of the original stream as well as the overhead associated with header data. Long data streams (i.e., streams containing large packets) result in higher transmission efficiency since less packets are transmitted. However, long streams also result in higher end-to-end delay and packet loss since a lost packet results in the inability to re-create the stream at the receiver. Shorter streams are more tolerant of packet loss and have shorter end-to-end delay, because a packet lost does not necessarily affect stream re-creation at the receiver. This results in better preserved voice quality [OTSM02]. The length of the data streams is fixed in this study to one VoIP packet coded using the G.711 codec.

3.7.2 Number of Data Streams. As the load on the MANET increases, OLSR performance is observed. Since VoIP traffic is sensitive to delay and packet loss, it is important to study the effects of increasing VoIP traffic over a MANET. As more traffic is injected into the network, the routing protocol must service multiple route requests. In addition to route requests, each node must accept traffic it receives and continue to forward packets through the network. Section 3.8 discusses the number of data streams as a factor for this study.

3.7.3 Packet Size. In general, packet size can vary between data streams. However, VoIP packets do not vary significantly since VoIP packet size is constant prior to transmission due to the codec used [OTSM02]. If they did vary, it could affect the performance results of the MANET. Packet size for this study is fixed at 200 bytes.

3.7.4 Codec. The rate at which the data stream is sampled is important since it affects the performance of the VoMAN system. Different codecs sample at different rates which results in various packet sizes [VSMH02]. Various compression ratios create variances in data streams such that two data streams carrying the same information sampled at different rates can vary greatly in size. The codec in this study is the G.711 8-bit PCM codec commonly used in voice applications.

3.8 Factors

Factors are the parameters that are varied during analysis to observe their effect on the performance metrics. The factors of node density, number of data streams, and mobility are varied in this study. Table 3.2 lists the factors and their levels. The levels of each factor are chosen in order to observe the impact of each factor on the OLSR routing protocol.

3.8.1 Node Density. Since the simulation area is fixed for all scenarios, the number of nodes in each scenario (10, 30 or 50) fit in the 1,000 m by 1,000 m area.

3.8.2 Number of Data Streams. This factor level is 1, 10, or 25 streams. The data streams are identical 200 byte packets sampled using the G.711 codec. As the

Table 3.2: Factors and Their Levels

Factor	**Units**	**Levels**
Node Density	number of nodes	10, 30, 50
Number of Data Streams	number of streams	1, 10, 25
Mobility	n/a	mobile, static

number of streams in the network increases, the performance of OLSR should affect delay and packet loss. These streams originate from a source node, `Mobile_1`, and travel to randomly chosen destinations in the MANET. These random destinations are chosen by the random destination selector in OPNET.

3.8.3 Mobility. When nodes are static, nodes in the network have no trajectory, thus they remain in their initial position throughout the simulation period. When the nodes are mobile, every node in the network has a randomly-generated trajectory with a maximum speed of 3 MPH. This simulates an airport environment where the average human walking speed is 3 MPH [You99]. These random trajectories are chosen by OPNET using the random waypoint mobility profile. Appendix A covers mobility settings for scenario creation in OPNET. Nodes using random waypoint mobility are not assigned trajectories that result in the node traveling outside the simulation area. Therefore, all nodes remain in the simulation area throughout the simulation period.

3.9 Evaluation Technique

Measurement of an actual MANET is expensive and infeasible. Therefore, the evaluation technique is simulation in OPNET.

3.9.1 OPNET. Simulations are run using OPNET modeler version 14.5.A PL0 (Build 7017 64-bit) on Linux. Ad hoc wireless network scenarios are created with random node placement in a 1,000 m by 1,000 m area using the `manet_station_adv` node model adjusted to meet the goals of the experiment. Table 3.3 lists the node attributes adjusted for this study. The nodes are randomly placed in the simulation area by OPNET's random node placement feature. The simulation time is one day and the simulation kernel used is the optimized 32-bit sequential kernel. The simulation kernel only accounts for the event scheduler and kernel procedure implementation. Appendix A explains the OPNET simulation setup in detail.

VoIP traffic is introduced into the network with constant packet size of 1,600 bits (200 bytes) and an exponential inter-arrival time starting at 0.0 sec with the stop time being the end of simulation. OLSR parameters used in OPNET are shown in Table 3.4.

3.9.2 Validation. The OPNET model is validated by running test cases where no routing protocol is used with two nodes in the ad hoc network. Using IEEE 802.11g for the MAC layer, 10 VoIP data streams are sent across the network from node 1 to node 2. The size of the streams are fixed at 200 bytes while the distance between the nodes is increased from 10 m to 600 m in various increments resulting in a total of 14 different tests. As shown in Table 3.5, packet loss begins when the nodes approach 400 m of separation and increases as the distance increases. At approximately 550 m apart, the nodes drop more than 99% of all packets, and at 566 m, 100% packet loss is reached.

Table 3.3: OPNET: manet_station_adv Node Model Attributes

Parameter	**Setting**
Routing Protocol	OLSR
Area	1,000 m by 1,000 m
Node placement	random
Power	0.020 W
MAC layer	802.11g
Data rate	54 Mbps
PCF/HCF	disabled
Mobility	Random waypoint at 3 MPH

Table 3.4: OLSR Parameters in OPNET

Parameter	**Setting**
Willingness	default
HELLO interval	2 sec
TC interval	5 sec
Neighbor hold time	6 sec
Topology hold time	15 sec
Duplicate message hold time	30 sec
Internet Protocol	IPv4

Throughput for these test cases is consistent with IEEE 802.11g standards. Table 3.5 lists the expected maximum throughput for IEEE 802.11g environments [IEE03] compared to the observed results from OPNET. The expected maximum throughput for IEEE 802.11g environments is only available to 300 ft since 802.11g should not work after this distance. However, in OPNET, a transmission range of 371 m is available [GMC08]. The observed throughput for less than 300 ft never exceeds the maximum throughput for 802.11g.

Table 3.5: OPNET Validation Results

Distance (feet)	**Distance** (meters)	**Maximum Throughput** (Mbps) [IEE03]	**Observed Throughput** (Kbps)	**Packet Loss**
10.00	3.048	24.7	17.6	0.00%
50.00	15.24	24.7	17.6	0.00%
100.00	30.48	19.8	17.6	0.00%
150.00	45.72	12.4	17.6	0.00%
200.00	60.96	4.9	17.6	0.00%
250.00	76.20	1.6	17.6	0.00%
300.00	91.44	0.9	17.6	0.00%
1000.00	304.80	-	17.6	0.00%
1312.34	400.00	-	17.6	0.00%
1476.38	450.00	-	17.6	0.00%
1640.42	500.00	-	8.7	50.35%
1804.46	550.00	-	0.0	99.94%
1856.96	566.00	-	0.0	100.00%
1968.50	600.00	-	0.0	100.00%

3.10 Experimental Design

A full-factorial experimental design with an 80% confidence interval is used. Eighteen different scenarios are considered using all possible factor combinations. Using pseudo-random numbers for seed values, a total of

$$(\underbrace{5}_{\text{repetitions}} \times \underbrace{5}_{\text{scenarios}}) + (\underbrace{10}_{\text{repetitions}} \times \underbrace{13}_{\text{scenarios}}) = 155 \qquad (3.1)$$

total experiments are run. The seed values in Table 3.6 are manually entered into OPNET. Table A.2 in Appendix A lists the number of repetitions used for each scenario. Not all scenarios are repeated 10 times due to time constraints. Table A.3 in Appendix A lists the average run times for each scenario.

Table 3.6: Seed Values

149	953	811	1019	37	17	397	683	277	977

The following assumptions are valid for this study:

- All nodes in the network use the same wireless interface, which is modeled after the Cisco Aironet 802.11A/B/G wireless cardbus adapter.
- Battery life is not considered in this study.
- All traffic originates from one source node, `Mobile_1`, and travels to random destinations within the MANET.
- All VoIP data streams are identical with a packet size of 200 bytes using codec G.711.
- The network area is fixed at 1,000 m by 1,000 m.
- Background traffic is not considered and it is assumed that no background traffic exists in the MANET.
- It is assumed that the simulation environment is outdoor and does not contain obstacles.

3.11 Summary

Through OPNET simulation, this study investigates the performance of MANETs implementing VoIP. Specifically, this research examines whether routing protocols affect VoIP performance over MANETs. The system under test is the VoIP MANET (VoMAN) system with the routing protocol (OLSR) being the component under test. VoMAN provides the service of VoIP calls over a MANET.

The metrics considered in this study are end-to-end delay and packet loss. The factors varied in the experiment are node density, number of data streams, and mobility. Using a full-factorial design, 18 different scenarios and 155 total experiments using a workload of representative VoIP traffic with fixed packet lengths of 200 bytes using the G.711 codec are studied.

IV. Results and Analysis

4.1 Introduction

Results discussed in this chapter cover the overall experiment and concentrate on the main results and analysis obtained from the study. Section 4.2 discusses the impact of the number of nodes on delay and packet loss while Section 4.3 discusses the impact of the number of streams. Section 4.4 discusses the impact of mobility on delay and packet loss. Section 4.5 analyzes the results, and Section 4.6 summarizes the chapter. The raw data used for analysis are in Appendix B, while the detailed analysis, including individual scenario graphs, is in Appendix C. Outliers in the data are discussed in Section C.3 of Appendix C.

4.2 Impact of the Number of Nodes

Figure 4.1 compares delay in relation to the number of nodes. Overall, delay increases an average of 0.12 ms as the number of nodes increases. Specifically, the number of nodes affects delay for scenarios with one stream and static nodes. As the number of nodes increases from 10 to 30, delay increases 0.40 ms, and when the number of nodes increases to 50, delay increases an additional 0.21 ms. As the number of nodes increases from 10 to 30 for one stream with mobile nodes, delay decreases 0.15 ms. An increase of 0.07 ms is observed for static nodes with 10 streams as the number of nodes increases from 10 to 30. For the mobile nodes with 10 streams, an increase in delay of 0.02 ms is observed as the number of nodes increases from 10 to 30. This is likely due to the fact that as more nodes are added to the 1,000 m by 1,000 m area, OLSR is able to find better routes and thus reducing delay.

Figure 4.2 compares packet loss in relation to the number of nodes. The number of nodes does affect packet loss. For the majority of the cases, packet loss decreases an average of less than 1% when the number of nodes is increased from 10 to 30. As more nodes are added to the network, nodes are able to find multiple paths to their destination. This increases the routes that can be chosen thereby giving a packet a higher chance to re-route if it experiences link failures. When the number of nodes

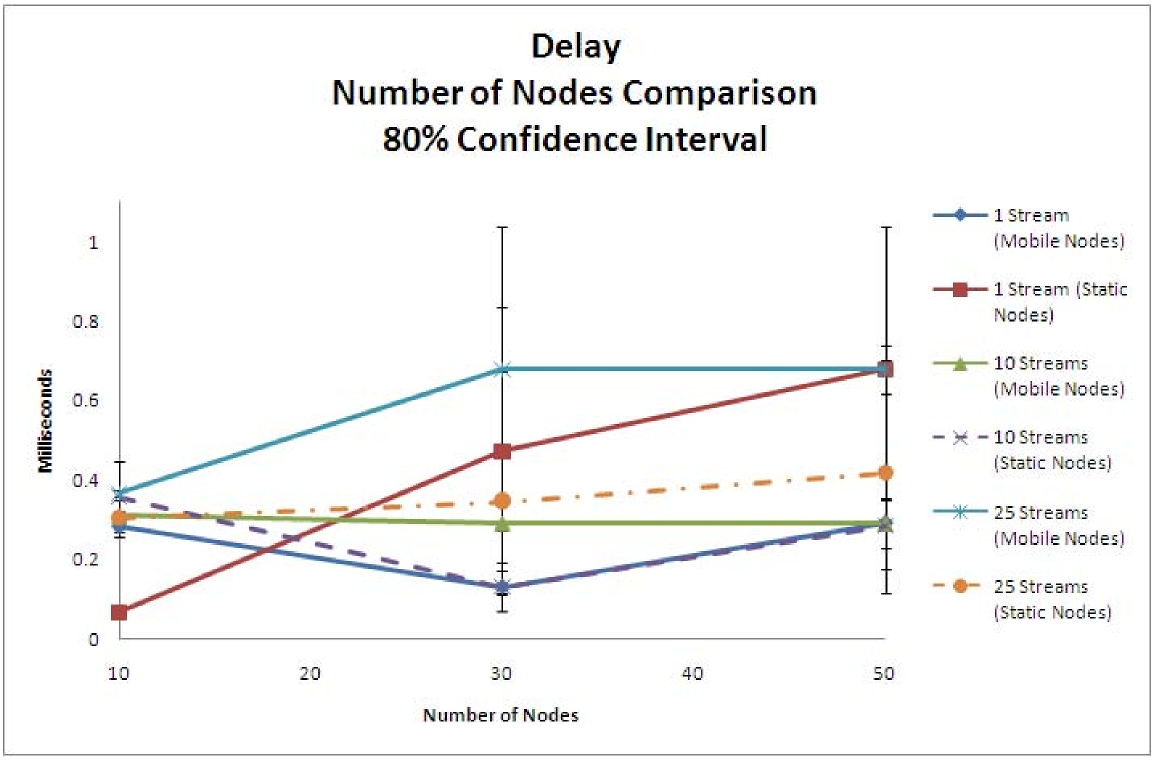


Figure 4.1: Delay Comparison Based on the Number of Nodes

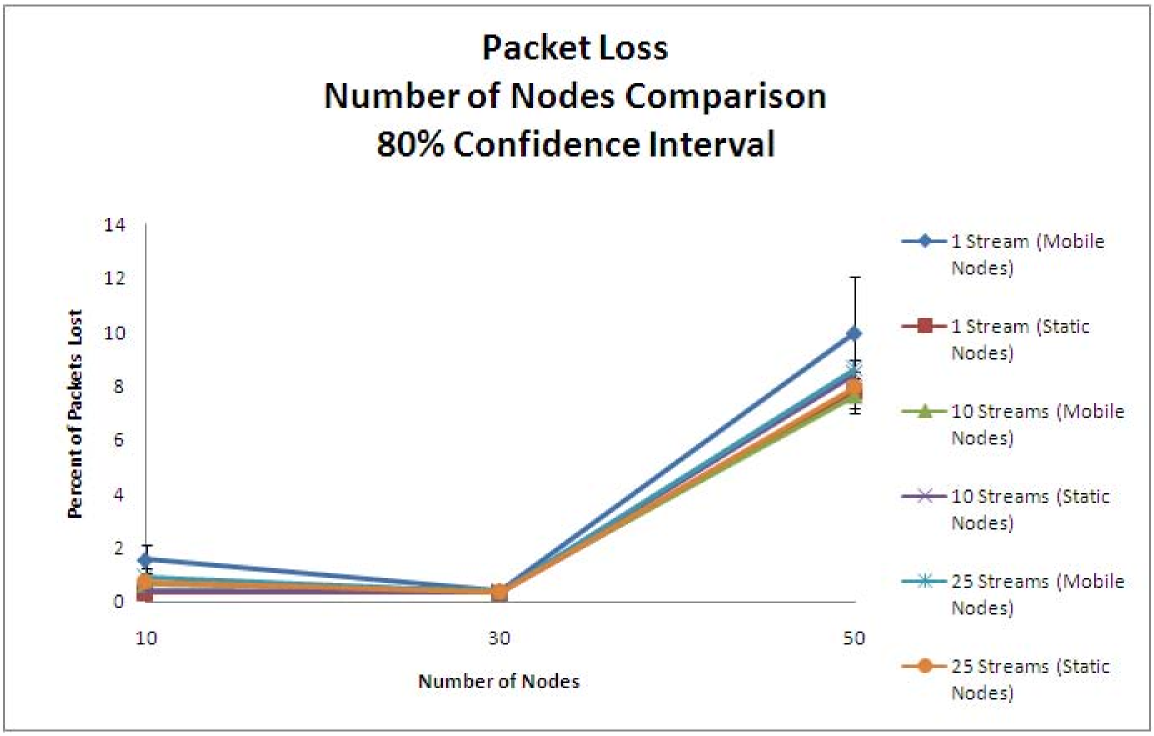


Figure 4.2: Packet Loss Comparison Based on the Number of Nodes

is increased from 30 to 50, all scenarios follow the trend of having an average packet loss increase of 8%. This increase in packet loss is due to the increase in the number of nodes in the network, because interference between the nodes is experienced as the number of nodes in a fixed simulation area increases. The network becomes saturated with nodes and OLSR can only support neighborhoods of up to 50 nodes [ABJ03].

4.3 Impact of the Number of Streams

Figure 4.3 displays the results of delay for mobile node cases relative to the number of data streams. Overall, delay increases an average of 0.13 ms as the number of streams increases from 1 to 25. Specifically, for 10 nodes, delay increases 0.03 ms as the number of streams increases from 1 to 10 and increases an additional 0.06 ms as the number of streams increases from 10 to 25. For 30 nodes, as the number of streams increases from 1 to 10, delay increases 0.16 ms and increases an additional 0.06 ms as the number of streams increases from 10 to 25. For 50 nodes, delay increases 0.36 ms as the number of data streams increases from 10 to 25.

Figure 4.4 displays the results for the static node cases in relation to the number of data streams. For these cases, delay does not consistently increase. However, delay has an average increase of 0.04 ms as the number of streams increase from 1 to 25. Since the nodes are static, routes are calculated during initial network setup by OLSR and do not need to be re-calculated. Since the routes are already established, delay is not increased.

Figure 4.5 compares packet loss in relation to the number of data streams. A statistically significant difference in packet loss of 8.41% occurs between the scenario with 10 mobile nodes and 10 data streams and the scenario with 50 mobile nodes and 10 data streams. A 7.45% difference in packet loss is observed for the case with one data stream as the static nodes increases from 30 to 50. Likewise, this same 7.45% difference in packet loss can be observed between 10 static nodes with one data stream and 50 static nodes with one data stream. For each scenario, the number of streams does affect packet loss.

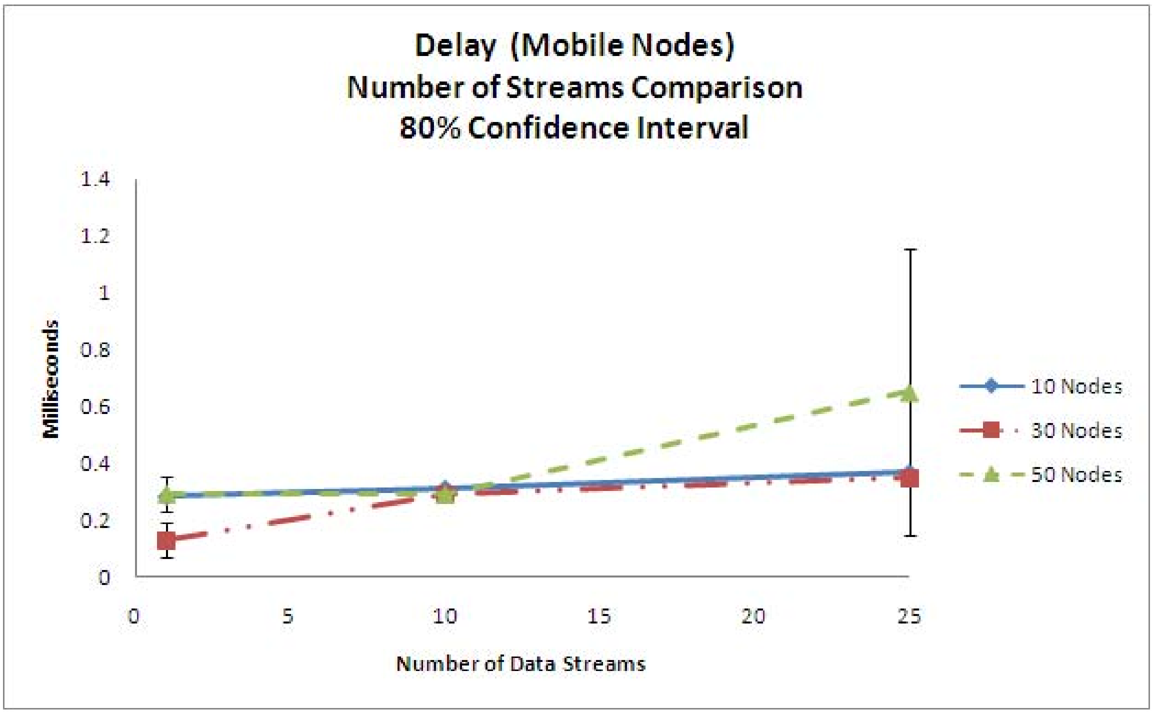


Figure 4.3: Delay Comparison Based on the Number of Streams - Mobile Nodes

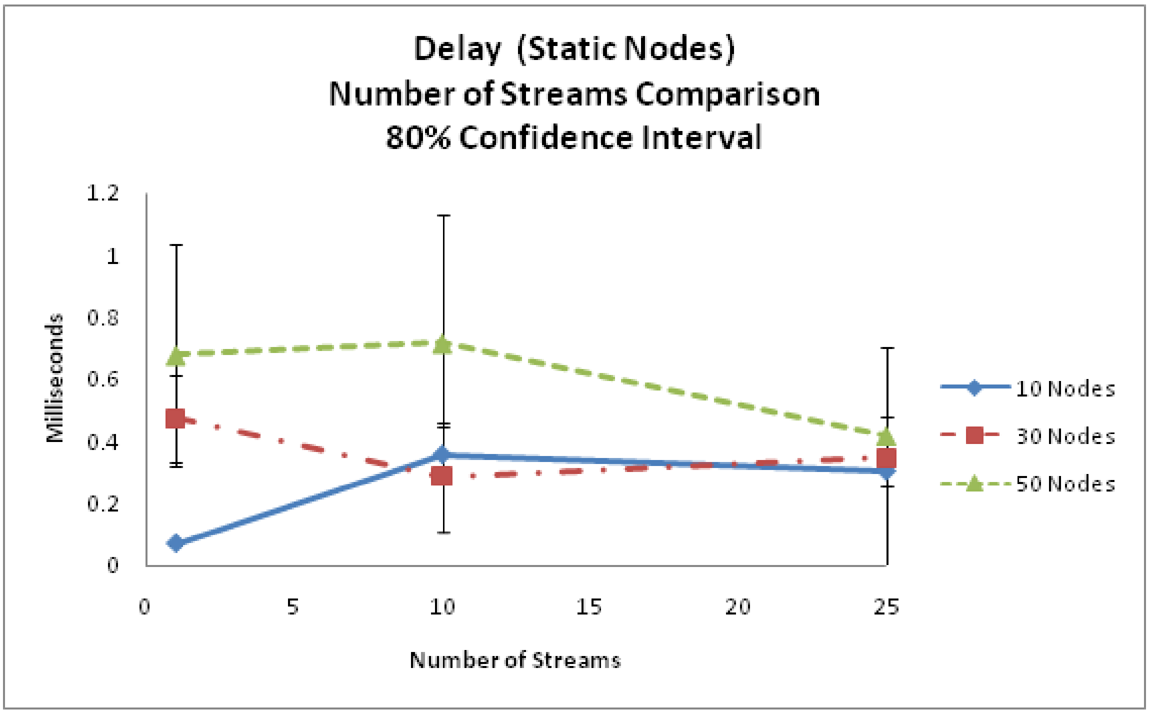


Figure 4.4: Delay Comparison Based on the Number of Streams - Static Nodes

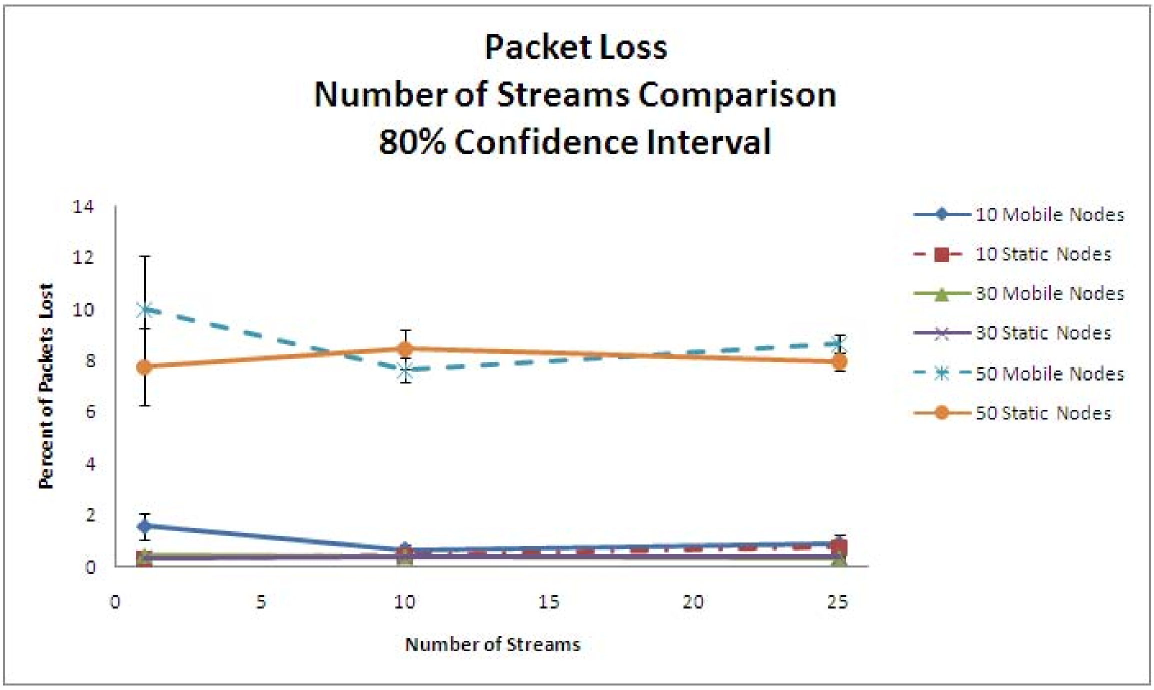


Figure 4.5: Packet Loss Comparison Based on the Number of Streams

The largest change in packet loss for one scenario can be observed in the 50 mobile node cases. Packet loss actually decreases 2.32% as the number of streams increases from 1 to 10, and then increases an additional 0.99% as the number of streams increases from 10 to 25.

4.4 Impact of Mobility

Figure 4.6 compares the effect of mobility on delay. Delay 0.08 ms lower for mobile scenarios than for static scenarios. The means are not different between the static and mobile node scenarios since the probability of difference has a one-sided p-value of 0.388.

Figure 4.7 compares the effect of mobility on packet loss. Packet loss is 1.15% higher for mobile scenarios than for static scenarios. The means are different between the static and mobile node scenarios with a one-sided p-value of 0.083.

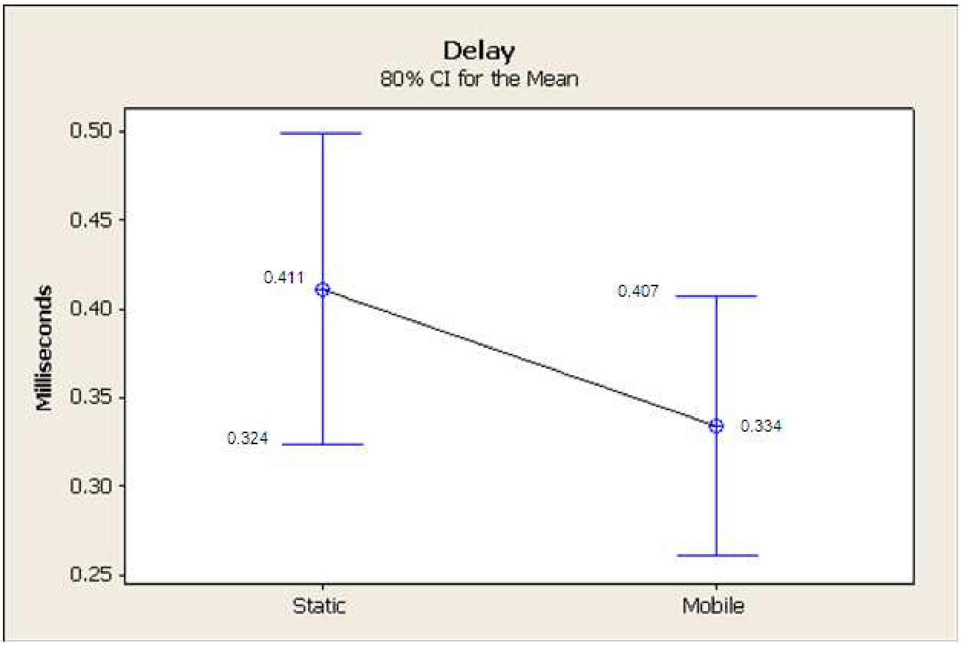


Figure 4.6: Delay Results Comparing Static and Mobile Scenarios

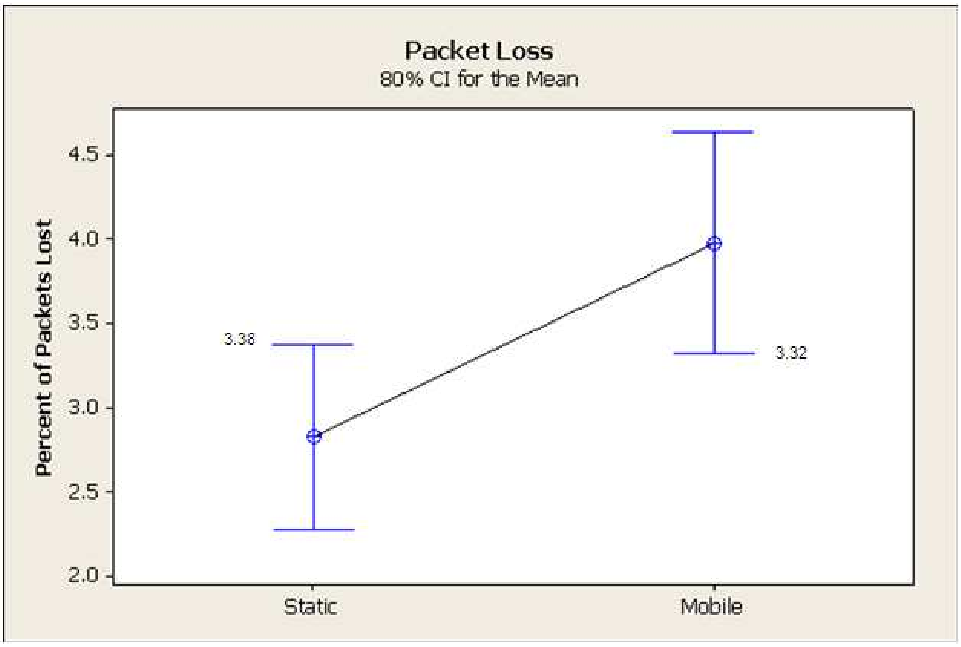


Figure 4.7: Packet Loss Results Comparing Static and Mobile Scenarios

4.5 Analysis

Node density, number of data streams and mobility affect delay and packet loss. As the number of data streams increases, both delay and packet loss also increases. Node density has different affects on delay and packet loss; it decreases delay while providing interesting results for packet loss.

Node density decreases packet loss as the number of nodes increases from 10 to 30, but then increases packet loss for scenarios with 50 nodes. This is due to the relationship of the number of nodes in the given area. Since the simulation area is fixed to 1,000 m by 1,000 m, the 10 node scenarios do not have enough nodes to choose the best possible MPR nodes. Therefore, OLSR cannot take advantage of the available optimizations over the classic link state algorithm. Every node is required to be an MPR, thus reducing OLSR to classic link state.

For the scenarios with 30 nodes in a 1,000 m by 1,000 m area, OLSR is able to select MPRs in a more advantageous manner such that packet loss is decreased. However, by increasing the number of nodes to 50, OLSR efficiency is reduced by sending and processing more overhead traffic.

As the number of nodes increases, delay also increases. A few cases result in a decrease in delay, due to more nodes being added to the MANET. Thus, OLSR is able to find best paths since its metric for route selection is shortest path (i.e., shortest number of hops from source to destination) [JMC$^+$01] resulting in paths with shorter propagation delays thus decreasing overall end-to-end delay.

The number of data streams affects both delay and packet loss. This is expected since as more traffic is injected into the MANET, there is a higher likelihood of packet loss and increased delay. For a given MANET, less traffic results in OLSR having low packet loss and delay.

4.6 Summary

The performance of MANETs running OLSR while VoIP traffic is introduced into the network is observed. The differences in data points are not statistically significant since the confidence intervals overlap. However, from the results, it is observed that node density, number of data streams, and mobility tend to affect delay and packet loss.

V. Conclusions

This study observes the performance of MANETs running OLSR while VoIP traffic is introduced into the network. It determines the suitability of OLSR as a routing protocol for MANETs running a VoIP application. The goal of this research is to determine whether routing protocols affect VoIP end-to-end delay and packet loss in MANETs.

Representative VoIP traffic is submitted to a MANET and end-to-end delay and packet loss are observed. Node density, number of data streams and mobility are varied creating a full-factorial experimental design of 18 distinct scenarios. OPNET modeler simulates the MANET, and VoIP traffic is introduced using one source node that sends traffic to random destinations throughout the network.

5.1 Conclusions

Results show that node density, number of data streams, and mobility affect delay and packet loss. Even with the increase in both packet loss and delay, OLSR is still a suitable routing protocol for VoIP traffic. Delays between 0.069 ms to 0.717 ms are significantly below the recommended average 150 ms for VoIP applications. This could increase as more traffic is introduced into the MANET; however, it is still well below the recommended 150 ms. Background traffic is not considered in this experiment but would also increase delay. Packet loss is between 0.32% and 9.97%, which is less than the acceptable 10% for VoIP conversations.

These results show that routing protocols do, in fact, affect delay and packet loss in MANETs and that OLSR is quite suitable for routing VoIP traffic in MANETs.

5.2 Future Work

Future work can include studying scenarios where the amount of traffic introduced into the MANET is increased to the point that OLSR can no longer provide acceptable delay and packet loss results. This can be accomplished by overloading the network with VoIP traffic. By increasing the amount of VoIP streams into the

network, it can be determined whether OLSR begins to increase delay and packet loss to the extent that the MANET can no longer support VoIP applications.

A prioritization study involving a MANET with a mixture of VoIP and non-time sensitive traffic could provide interesting results. This study would determine if OLSR is able to handle routing time-sensitive traffic such as VoIP amidst regular non-time sensitive traffic. MANETs that use OLSR as the routing protocol and are able to transmit non-time sensitive data could introduce VoIP traffic into this network and observe whether OLSR is still able to maintain delay and packet loss below the recommended values.

Since simulation results tend to assume best case scenarios and perfect conditions, an ad hoc testbed using OLSR to route VoIP traffic could determine whether OLSR can still support VoIP applications when implemented outside a simulation environment.

5.3 Relevance of Work

MANETs are becoming common choices for networks, especially where infrastructure-based networks are infeasible. As the popularity of MANETs continue to grow, the capabilities of MANETs must be investigated. Having a MANET able to transmit real-time voice traffic, such as VoIP, is a valuable asset for the military as well as the commercial market.

Appendix A. OPNET Simulation Setup

The following steps are needed in order to create and run a simulation in OPNET:

1. Create Project
2. Create Scenario
3. Add VoIP Packets
4. Configure Discrete Event Simulation (DES)
5. Run Simulation

The remainder of this appendix describes how to accomplish these steps. Section A.1 overview scenario creation and setup. Section A.2 details how VoIP packets are added to the MANET, while Section A.3 discusses the configuration of the DES sequence. Section A.4 provides a detailed view of how the scenarios are arranged in OPNET. Section A.5 describes the repetitions for each scenario and Section A.6 lists the average run times for each scenario.

A.1 Scenario Creation and Setup

Deploying the wireless network in the scenario can be done using a saved configuration file. Table A.1 shows the fields that are changed in the XML configuration file (Listing A.1) to create the various scenarios used in this study.

Table A.1: Fields Changed in XML File for Scenario Creation

Field	Static	Mobile
`ss_num_nodes`	10, 30, 50	10, 30, 50
`Trajectory Information`	none	random waypoint (auto create)
`Number of Nodes`	n/a	10, 30, 50
`Speed (m/s)`	n/a	3.00
`Area of Movement`	n/a	within network

Listing A.1: XML Configuration File - Set for a 10 Mobile Node Scenario

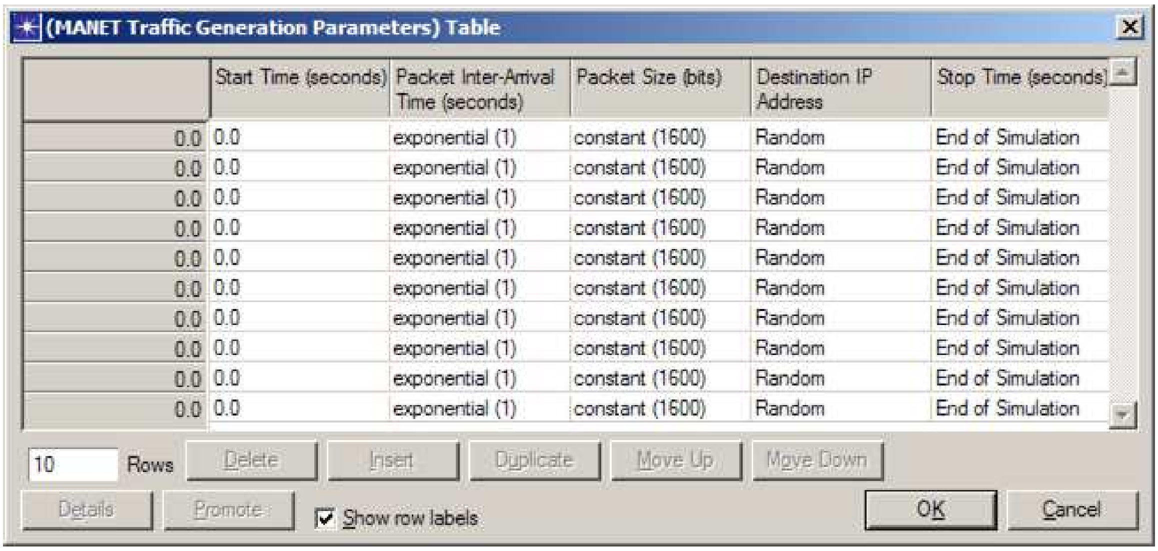
```
<?xml version="1.0" encoding="UTF-8" standalone="no" ?>
- <Wireless_Wizard_Configuration>
- <WelcomeStage>
- <BaseInformation>
<sp name="use_wizard" value="true" />
</BaseInformation>
</WelcomeStage>
- <LocationStage>
- <BaseInformation>
<sp name="location_coordinates" value="X / Y" />
<sp name="create_subnet" value="false" />
</BaseInformation>
- <TablesInformation>
- <TableInformation name="location_table">
- <TableRow>
<sp name="X" value="500.000006" />
</TableRow>
- <TableRow>
<sp name="Y" value="500.00" />
</TableRow>
</TableInformation>
</TablesInformation>
</LocationStage>
- <TechnologyStage>
- <BaseInformation>
<sp name="choose_tech" value="WLAN (Ad-hoc)" />
</BaseInformation>
- <TablesInformation>
- <TableInformation name="tech_params_table">
- <TableRow>
<sp name="Node Transmission Power (W)" value="0.02" />
</TableRow>
- <TableRow>
<sp name="Operational Mode" value="802.11g" />
```

```
  </TableRow>
- <TableRow>
  <sp name="Data Rate" value="54 Mbps" />
  </TableRow>
- <TableRow>
  <sp name="Ad-hoc Routing Protocol" value="OLSR" />
  </TableRow>
  </TableInformation>
  </TablesInformation>
  </TechnologyStage>
- <TopologyStage>
- <BaseInformation>
  <sp name="topology_type" value="None" />
  <sp name="node_placement_type" value="Random" />
  </BaseInformation>
- <TablesInformation>
- <TableInformation name="topology_table">
- <TableRow>
  <sp name="Area (square meters)" value="1000000.00" />
  </TableRow>
  </TableInformation>
  </TablesInformation>
  </TopologyStage>
- <NodeSpecificationStage>
- <BaseInformation>
  <sp name="bs_num_nodes" value="0" />
  <sp name="ss_num_nodes" value="10" />
  <sp name="bs_name_tag" value="Access Point" />
  <sp name="ss_name_tag" value="Mobile Node" />
  <sp name="bs_prefix" value="Access Point" />
  <sp name="ss_prefix" value="Mobile" />
  <sp name="bs_model" value="wlan_ethernet_router" />
  <sp name="ss_model" value="manet_station" />
  <sp name="core_net_create" value="false" />
  </BaseInformation>
```

```
</NodeSpecificationStage>
- <MobilityStage>
- <TablesInformation>
- <TableInformation name="mobility_table">
- <TableRow>
<sp name="Trajectory Information" value="Random Waypoint (Auto ...
   Create)" />
<sp name="Number of Nodes" value="10" />
<sp name="Speed (m/s)" value="3.00" />
<sp name="Area of Movement" value="Within Network" />
<sp name="Altitude (m)" value="0.00" />
</TableRow>
</TableInformation>
</TablesInformation>
</MobilityStage>
</Wireless_Wizard_Configuration>
```

A.2 VoIP Packets

VoIP packets are added using the MANET traffic generation attribute under the source node (`Mobile_1`). Figure A.1 shows the MANET traffic generation attribute adjusted for 10 packets.



	Start Time (seconds)	Packet Inter-Arrival Time (seconds)	Packet Size (bits)	Destination IP Address	Stop Time (seconds)
0.0	0.0	exponential (1)	constant (1600)	Random	End of Simulation
0.0	0.0	exponential (1)	constant (1600)	Random	End of Simulation
0.0	0.0	exponential (1)	constant (1600)	Random	End of Simulation
0.0	0.0	exponential (1)	constant (1600)	Random	End of Simulation
0.0	0.0	exponential (1)	constant (1600)	Random	End of Simulation
0.0	0.0	exponential (1)	constant (1600)	Random	End of Simulation
0.0	0.0	exponential (1)	constant (1600)	Random	End of Simulation
0.0	0.0	exponential (1)	constant (1600)	Random	End of Simulation
0.0	0.0	exponential (1)	constant (1600)	Random	End of Simulation
0.0	0.0	exponential (1)	constant (1600)	Random	End of Simulation

Figure A.1: MANET Traffic Generation Attribute

A.3 DES Configuration

Figure A.2 shows the DES configuration for the scenario with 10 nodes, 10 streams and no mobility. DES is when the operation of a system is represented as a sequence of events. Web reports are generated for each scenario for data collection.

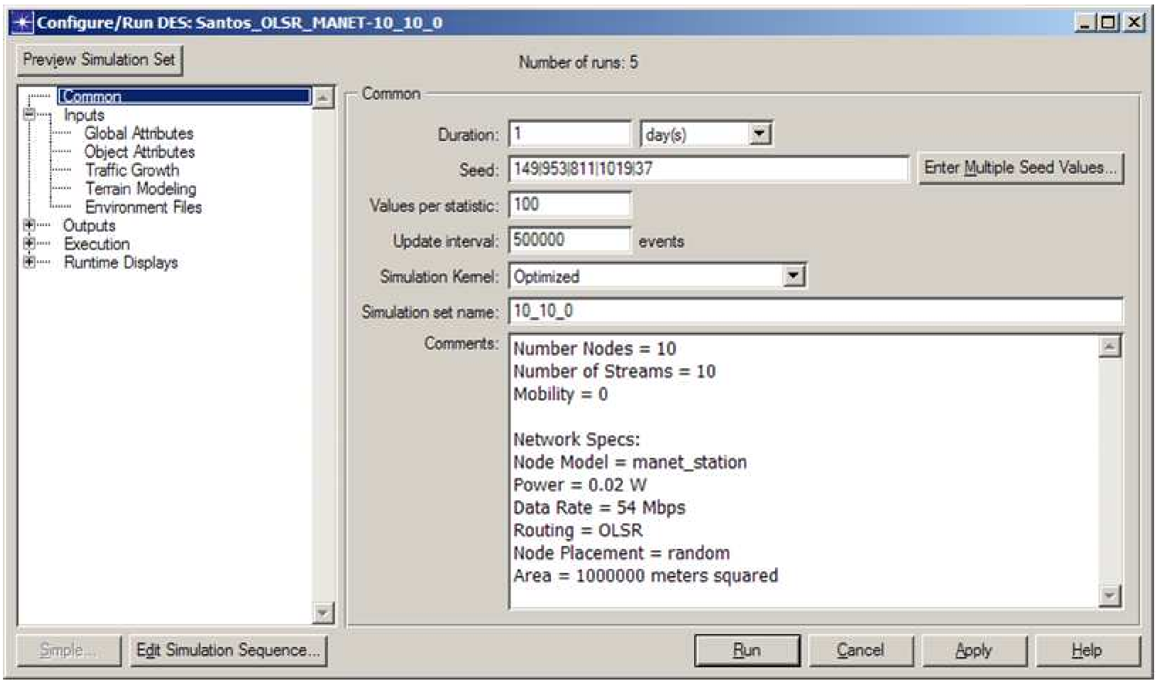


Figure A.2: DES Configuration

A.4 Scenarios

The figures in this section are screen shots of the scenarios simulated in OPNET. The nodes are placed randomly throughout the simulation area by OPNET. For the mobile scenarios, this is the state of the scenario at the beginning of the simulation. Each mobile scenario has various end states since the random waypoint mobility profile selects random trajectories and speeds at the time of simulation.

Figure A.3: 10 Static Nodes in OPNET

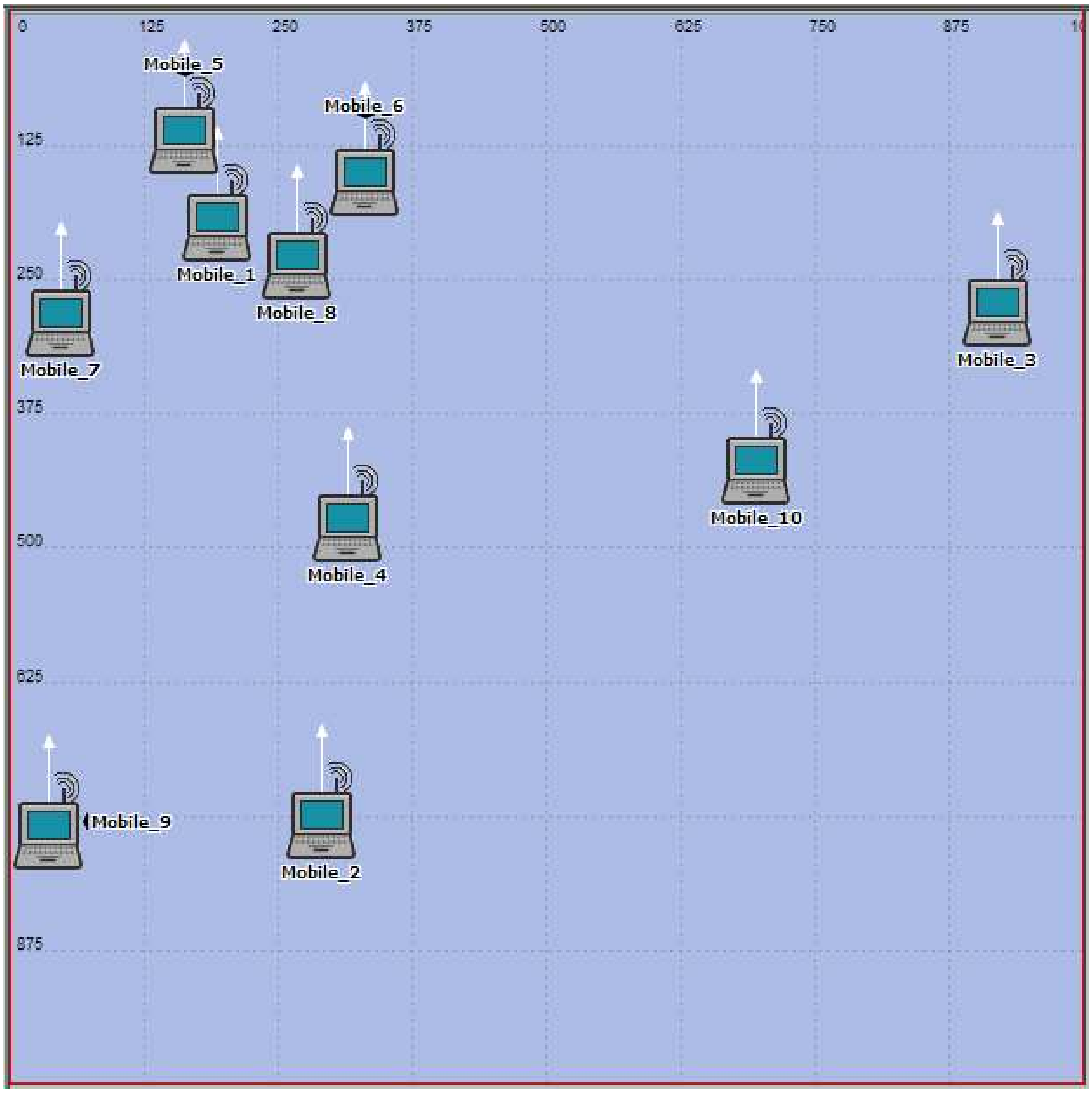


Figure A.4: 10 Mobile Nodes in OPNET

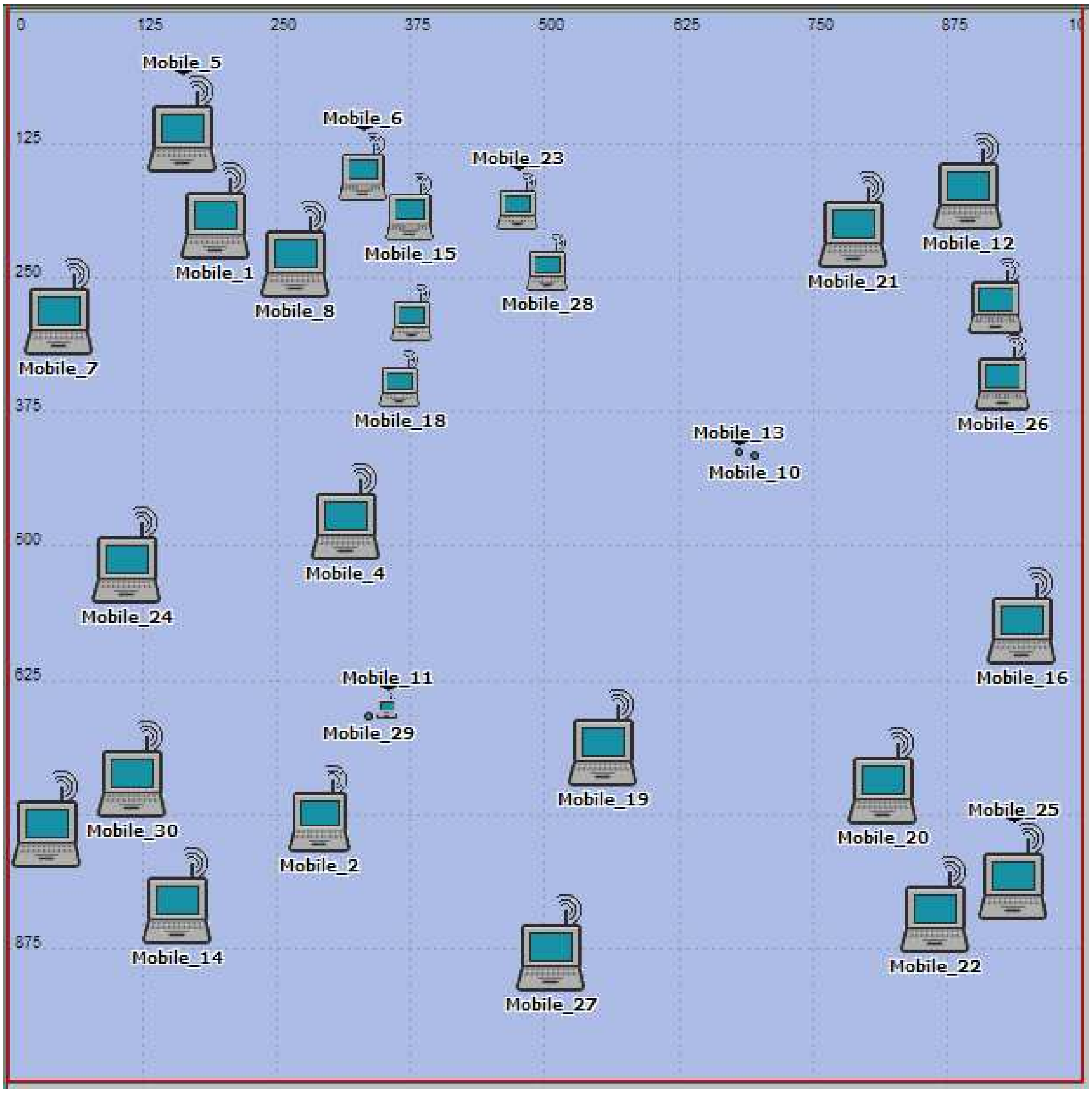


Figure A.5: 30 Static Nodes in OPNET

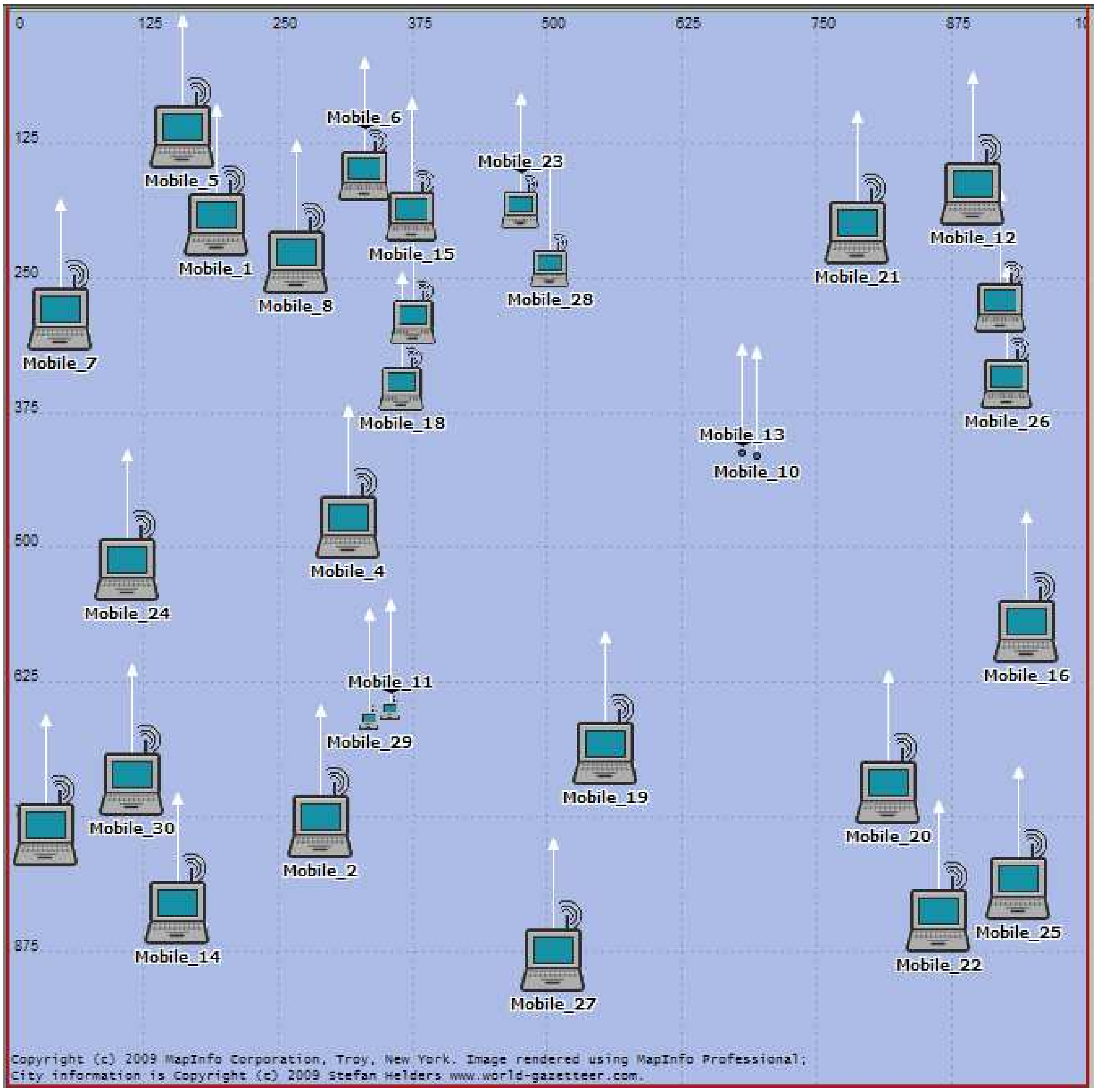


Figure A.6: 30 Mobile Nodes in OPNET

Figure A.7: 50 Static Nodes in OPNET

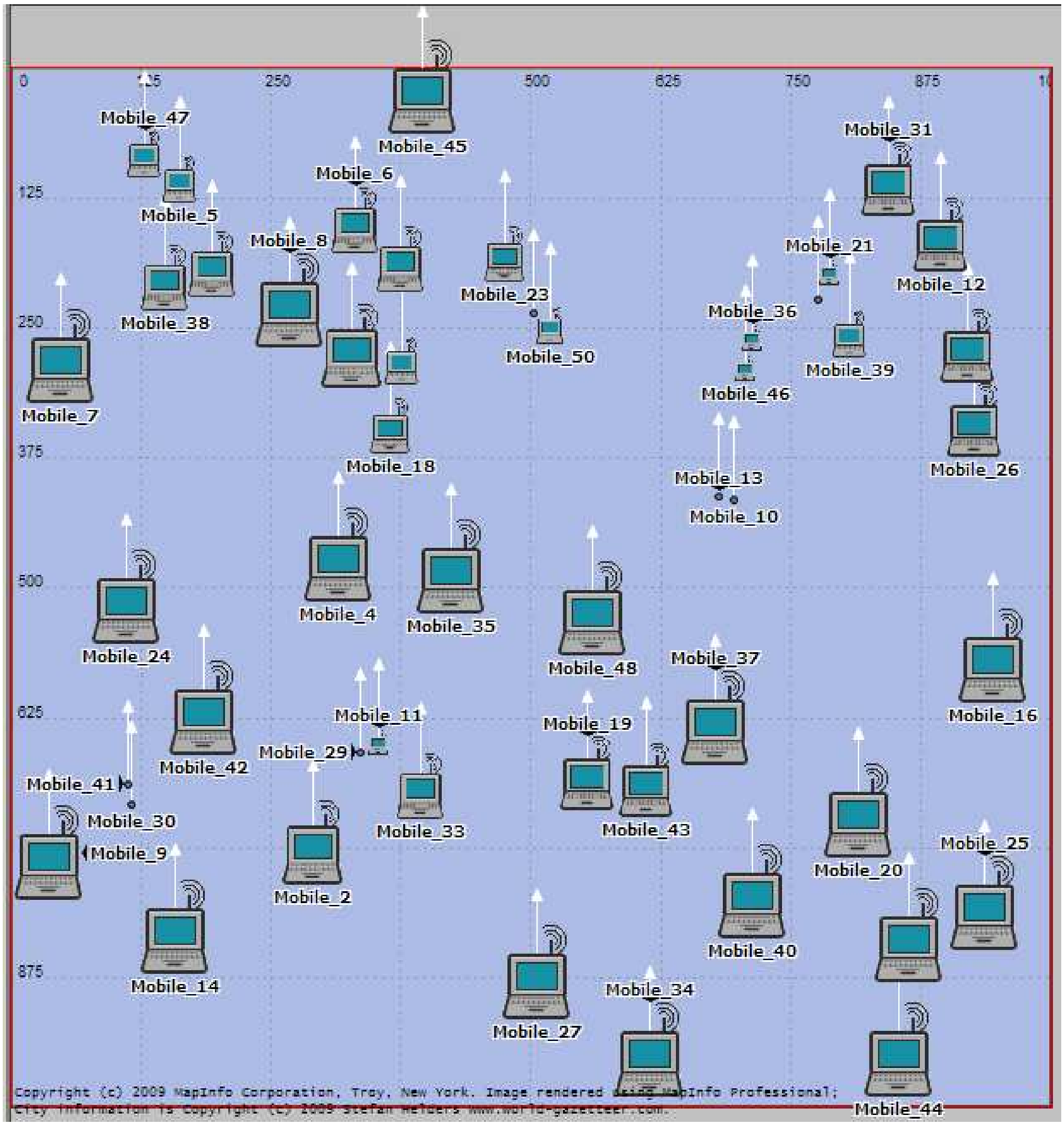


Figure A.8: 50 Mobile Nodes in OPNET

A.5 Scenario Repetitions

Table A.2 lists the number of repetitions run for each scenario. Not all scenarios are repeated 10 times due to time constraints.

Table A.2: Repetitions Run for Each Scenario

Scenario	**Repetitions**
10_1_0	5
10_1_1	10
10_10_0	10
10_10_1	5
10_25_0	10
10_25_1	10
30_1_0	10
30_1_1	10
30_10_0	10
30_10_1	5
30_25_0	10
30_25_1	5
50_1_0	10
50_1_1	10
50_10_0	10
50_10_1	10
50_25_0	5
50_25_1	10

A.6 Average Simulation Run Times

Table A.3 lists the average run times for each scenario. Run times ranged from 3 minutes to more than 8 hours.

Table A.3: Simulation Run Times

# of Nodes	# of Streams	Mobility	Average Run Time
10	1	0	3 min
10	1	1	3 min 30 sec
10	10	0	6 min
10	10	1	6 min 30 sec
10	25	0	10 min
10	25	1	11 min
30	1	0	1 hr
30	1	1	1 hr 7 min
30	10	0	1 hr 10 min
30	10	1	1 hr 20 min
30	25	0	1 hr 35 min
30	25	1	1 hr 40 min
50	1	0	6 hr 25 min
50	1	1	6 hr 30 min
50	10	0	6 hr 35 min
50	10	1	6 hr 40 min
50	25	0	8 hr
50	25	1	8 hr 30 min

The following is the raw data for all scenarios run in the experiment.

The scenarios are labeled in the following charts in the format "number of nodes"_"number of streams"_"mobility". For example, a 10 mobile node scenario with 10 data streams will be labeled as 10_10_1 and a 10 static node scenario with 10 data streams will be 10_10_0.

B.1 Packet Loss Data

Packet loss raw data is collected through OPNET in packets lost/second. This value is converted to percent of packets lost by

$$PercentPacketLoss = \frac{PL \times PS}{TS} \times 100 \tag{B.1}$$

where PL is packet loss obtained from OPNET, PS is packet size (constant at 1600 bits), and TS is the total amount of traffic sent.

Tables B.1, B.2, and B.3 show the raw packet loss data in percent of packets lost (converted using equation B.1). Table B.4 shows the analysis data obtained from Minitab.

Table B.1: Packet Loss Data for 10 Nodes

10_1_0	10_1_1	10_10_0	10_10_1	10_25_0	10_25_1
0.066721	0.3147	0.068722	0.30026	0.55516	0.3688
0.066524	0.2559	0.46375	0.30709	0.33806	0.394
0.066664	0.26687	0.68819	0.3094	0.33664	0.3669
0.078616	0.3018	0.27481	0.338	0.2557	0.36253
0.066693	0.2803	0.26733	0.2966	0.25998	0.3716
	0.2949	0.26881		0.16425	0.38924
	0.2809	0.47373		0.35947	0.3686
	0.2789	0.069819		0.2619	0.36828
	0.27912	0.48887		0.2539	0.3281
	0.2728	0.51239		0.2596	0.35383

Table B.2: Packet Loss Data for 30 Nodes

30_1_0	30_1_1	30_10_0	30_10_1	30_25_0	30_25_1
1.9758	0.27362	0.6564	0.29569	0.8333	0.34968
0.06709	0.21024	0.65196	0.29526	0.5205	0.34432
0.087641	0.25995	0.32737	0.28454	0.39316	0.34581
0.067119	0.2963	0.7958	0.27973	0.66991	0.35456
0.067969	0.26286	0.43305	0.30206	1.0385	0.34248
2.1078	5.85E-05	9.13E-05		0.000133	
0.079386	5.86E-05	8.47E-05		0.000136	
0.069075	5.85E-05	6.88E-05		0.000128	
0.13994	5.85E-05	8.32E-05		0.000126	
0.067476	5.86E-05	6.68E-05		9.95E-05	

Table B.3: Packet Loss Data for 50 Nodes

50_1_0	50_1_1	50_10_0	50_10_1	50_25_0	50_25_1
0.068581	0.4772	0.20825	0.2381	0.42371	0.1984
0.067884	0.4811	0.08453	0.3159	0.31863	0.3062
1.9364	0.2157	3.2952	0.2369	0.37027	0.2373
1.2477	0.2435	0.34694	0.297	0.5695	0.298
0.06834	0.07896	0.5647	0.3609	0.3991	3.917
0.068581	0.442	0.9926	0.2381		0.3854
0.067884	0.2357	0.26846	0.3159		0.2469
1.9364	0.3741	0.14072	0.2369		0.2795
1.2477	0.2341	0.5519	0.297		0.3543
0.06834	0.14	0.7191	0.3609		0.2888

Table B.4: Packet Loss Analysis Data from Minitab

Variable	Mean	StDev	Minimum	Median	Maximum	Range
10_1_0	0.06904	0.00535	0.06652	0.06669	0.07862	0.01209
10_1_1	0.28262	0.01713	0.2559	0.27971	0.3147	0.0588
10_10_0	0.3576	0.2012	0.0687	0.3693	0.6882	0.6195
10_10_1	0.31027	0.01633	0.2966	0.30709	0.338	0.0414
10_25_0	0.3045	0.1046	0.1643	0.2609	0.5552	0.3909
10_25_1	0.36719	0.01813	0.3281	0.36844	0.394	0.0659
30_1_0	0.473	0.828	0.067	0.074	2.108	2.041
30_1_1	0.1303	0.1389	0.0001	0.1051	0.2963	0.2962
30_10_0	0.286	0.327	0	0.164	0.796	0.796
30_10_1	0.29146	0.00909	0.27973	0.29526	0.30206	0.02233
30_25_0	0.346	0.402	0	0.197	1.039	1.038
30_25_1	0.34737	0.00481	0.34248	0.34581	0.35456	0.01208
50_1_0	0.678	0.82	0.068	0.069	1.936	1.869
50_1_1	0.2922	0.1424	0.079	0.2396	0.4811	0.4021
50_10_0	0.717	0.949	0.085	0.449	3.295	3.211
50_10_1	0.2898	0.05	0.2369	0.297	0.3609	0.124
50_25_0	0.4162	0.0942	0.3186	0.3991	0.5695	0.2509
50_25_1	0.651	1.149	0.198	0.293	3.917	3.719

B.2 Delay Data

Delay data obtained from OPNET is recorded in seconds. For the purpose of this research, all delay data is converted to milliseconds. Tables B.5, B.6, and B.7 show the raw delay data in milliseconds. Table B.8 shows the analysis data obtained from Minitab.

Table B.5: Delay Data for 10 Nodes

10_1_0	10_1_1	10_10_0	10_10_1	10_25_0	10_25_1
0.115684	1.274813	0.567766	0.624436	0.411874	0.490015
0.345362	1.846557	0.41699	0.463755	0.360784	2.886158
0.346115	0.579417	0.335261	0.404734	0.416693	0.398044
0.346345	0.580642	0.42772	0.694142	3.890738	0.698465
0.460471	4.736844	0.404877	1.098079	0.444347	1.110859
	1.038863	0.428165		0.319065	0.323839
	1.62117	0.370612		0.486696	0.531909
	1.157617	0.300624		0.365626	1.195255
	1.86452	0.55511		0.360931	0.346825
	0.923782	0.531795		0.402397	1.069173

Table B.6: Delay Data for 30 Nodes

30_1_0	30_1_1	30_10_0	30_10_1	30_25_0	30_25_1
0.692372	0.812888	0.405406	0.324332	0.32823	0.338229
0.576551	0.348236	0.392972	0.427389	0.439541	0.333434
0.115608	0.231799	0.38217	0.301158	0.38878	0.305763
0.231745	0.346529	0.324353	0.427936	0.333051	0.314352
0.345389	0.230991	0.289356	0.417148	0.444181	0.402783
0.232246	0.349778	0.370863		0.370067	
0.231764	0.346618	0.393151		0.384196	
0.579921	0.692954	0.35933		0.360578	
0.115041	0.231292	0.380919		0.328495	
0.116587	0.576384	0.440045		0.277805	

Table B.7: Delay Data for 50 Nodes

50_1_0	50_1_1	50_10_0	50_10_1	50_25_0	50_25_1
8.3333	13.613	10.91761	8.691738	8.210995	9.414795
2.7778	16.4929	10.29516	8.954819	7.439358	7.475215
5.535603	13.5246	5.860978	6.676531	7.5078	9.404899
11.25478	8.462566	8.33909	6.394939	8.138509	8.637147
10.9468	5.567989	8.364898	7.51043	8.588522	8.709476
8.3333	5.670571	5.890571	8.691738		8.101478
2.7778	13.99395	9.777332	8.954819		8.309379
5.535603	13.93936	8.674472	6.676531		9.78347
11.25478	5.581975	7.202196	6.394939		8.980145
10.9468	2.809797	9.083686	7.51043		7.550651

Table B.8: Delay Analysis Data from Minitab

Variable	Mean	StDev	Minimum	Median	Maximum	Range
10_1_0	0.3228	0.126	0.1157	0.3461	0.4605	0.3448
10_1_1	1.562	1.207	0.579	1.216	4.737	4.157
10_10_0	0.4339	0.0912	0.3006	0.4224	0.5678	0.2671
10_10_1	0.657	0.273	0.405	0.624	1.098	0.693
10_25_0	0.746	1.106	0.319	0.407	3.891	3.572
10_25_1	0.905	0.77	0.324	0.615	2.886	2.562
30_1_0	0.3237	0.2163	0.115	0.232	0.6924	0.5773
30_1_1	0.4167	0.2057	0.231	0.3474	0.8129	0.5819
30_10_0	0.3739	0.0422	0.2894	0.3815	0.44	0.1507
30_10_1	0.3796	0.0617	0.3012	0.4171	0.4279	0.1268
30_25_0	0.3655	0.0518	0.2778	0.3653	0.4442	0.1664
30_25_1	0.3389	0.0381	0.3058	0.3334	0.4028	0.097
50_1_0	7.77	3.41	2.78	8.33	11.25	8.48
50_1_1	9.97	4.84	2.81	10.99	16.49	13.68
50_10_0	8.441	1.717	5.861	8.52	10.918	5.057
50_10_1	7.646	1.088	6.395	7.51	8.955	2.56
50_25_0	7.977	0.491	7.439	8.139	8.589	1.149
50_25_1	8.637	0.786	7.475	8.673	9.783	2.308

C.1 Delay Analysis

C.1.1 10 Nodes. Figure C.1 shows delay results, in relation to the number of data streams, for the scenario with 10 static nodes. The means are not different between the 10 stream case and the 25 stream case since the probability of difference has a one-sided p-value of 0.468.

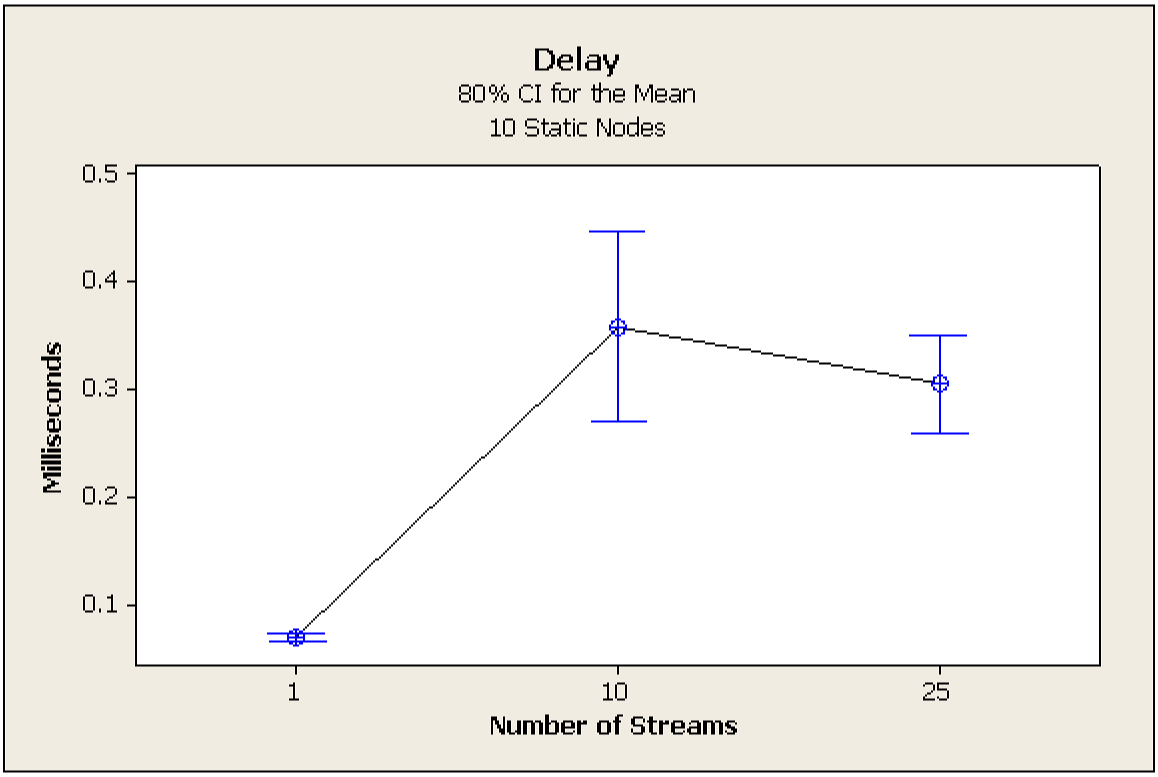


Figure C.1: Delay - 10 Static Nodes

Figure C.2 shows delay results, in relation to the number of data streams, for the scenario with 10 mobile nodes. The means are convincingly different between the 1 stream case and the 10 stream case with a probability of difference having a one-sided p-value of 0.010.

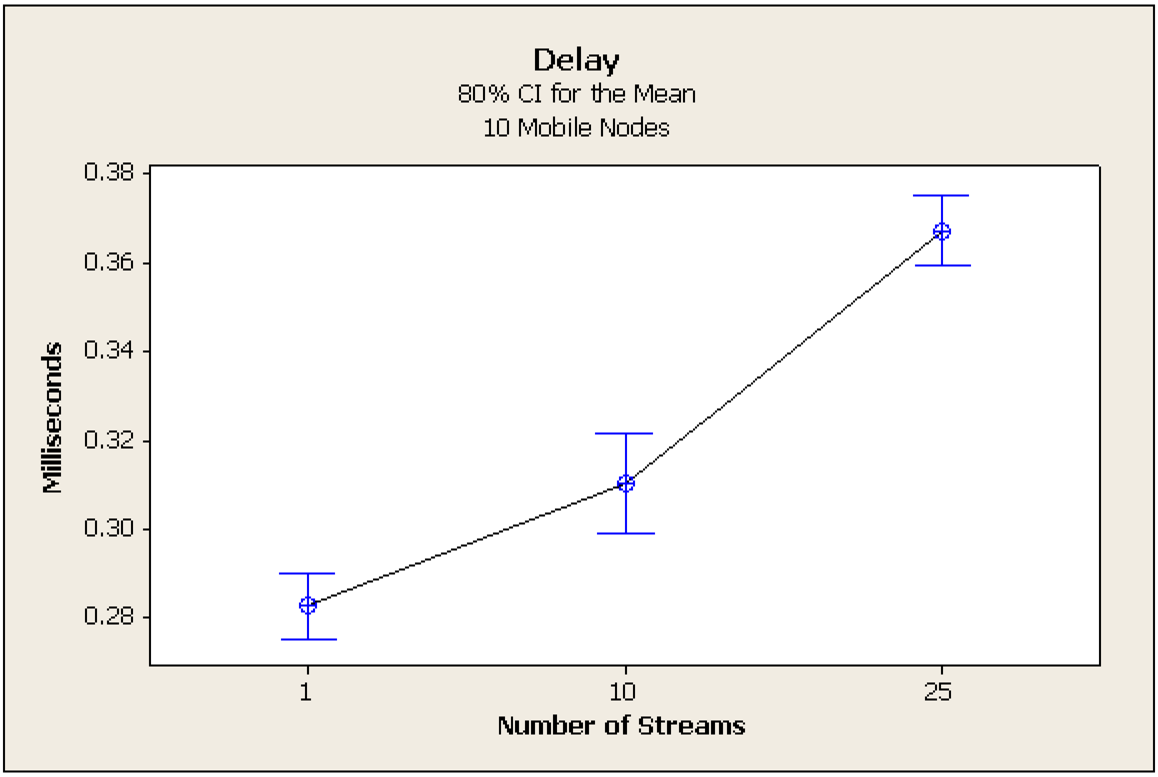


Figure C.2: Delay - 10 Mobile Nodes

C.1.2 30 Nodes. Figure C.3 shows delay results, in relation to the number of data streams, for the scenario with 30 static nodes. The means are not different since the probability of difference has a one-sided p-value of 0.754.

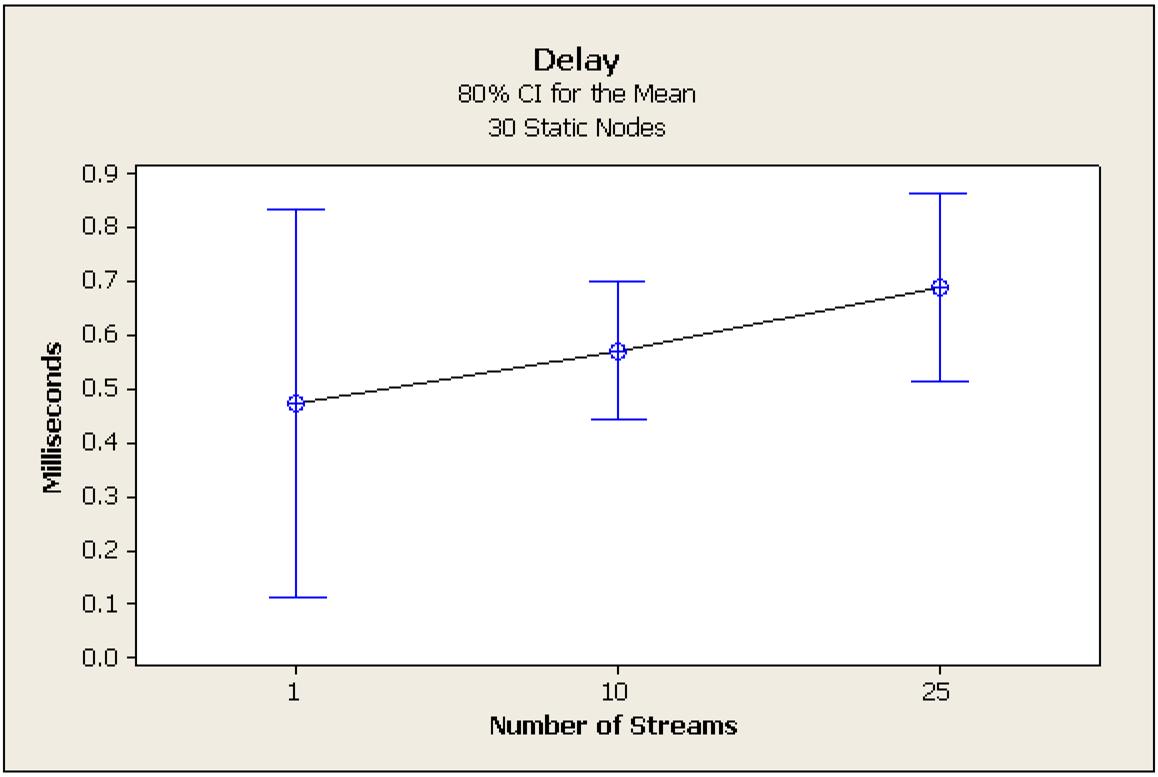


Figure C.3: Delay - 30 Static Nodes

Figure C.4 shows delay results, in relation to the number of data streams, for the scenario with 30 mobile nodes. The means are convincingly different between all cases with a probability of difference having a one-sided p-value of 0.002.

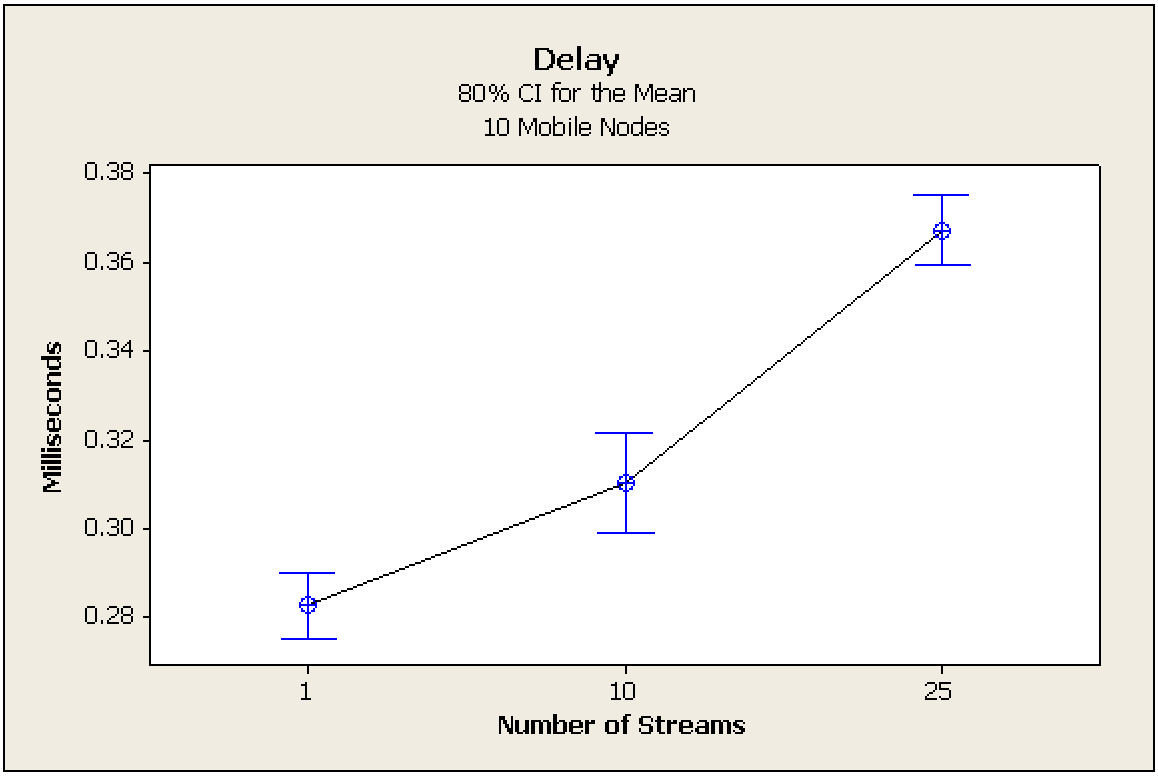


Figure C.4: Delay - 30 Mobile Nodes

C.1.3 50 Nodes. Figure C.5 shows delay results, in relation to the number of data streams, for the scenario with 50 static nodes. The means are not different since the probability of difference has a one-sided p-value of 0.780

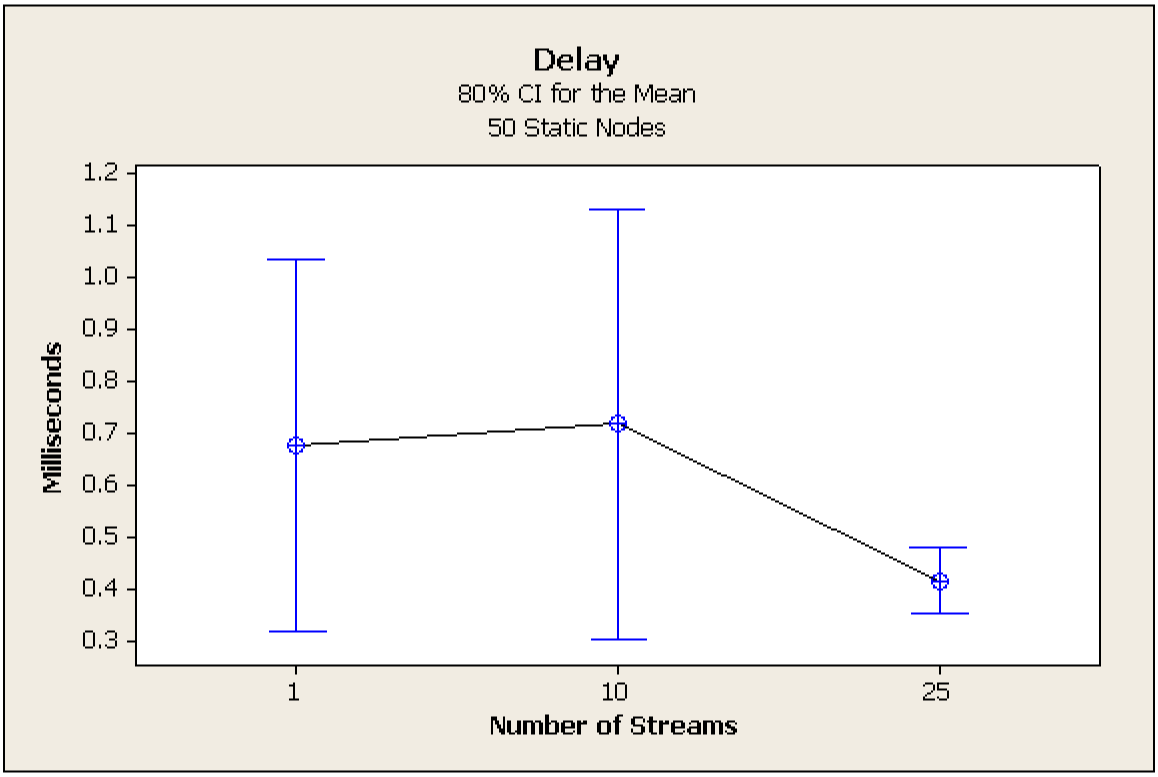


Figure C.5: Delay - 50 Static Nodes

Figure C.6 shows delay results, in relation to the number of data streams, for the scenario with 50 mobile nodes. The means are not different since the probability of difference has a one-sided p-value of 0.393.

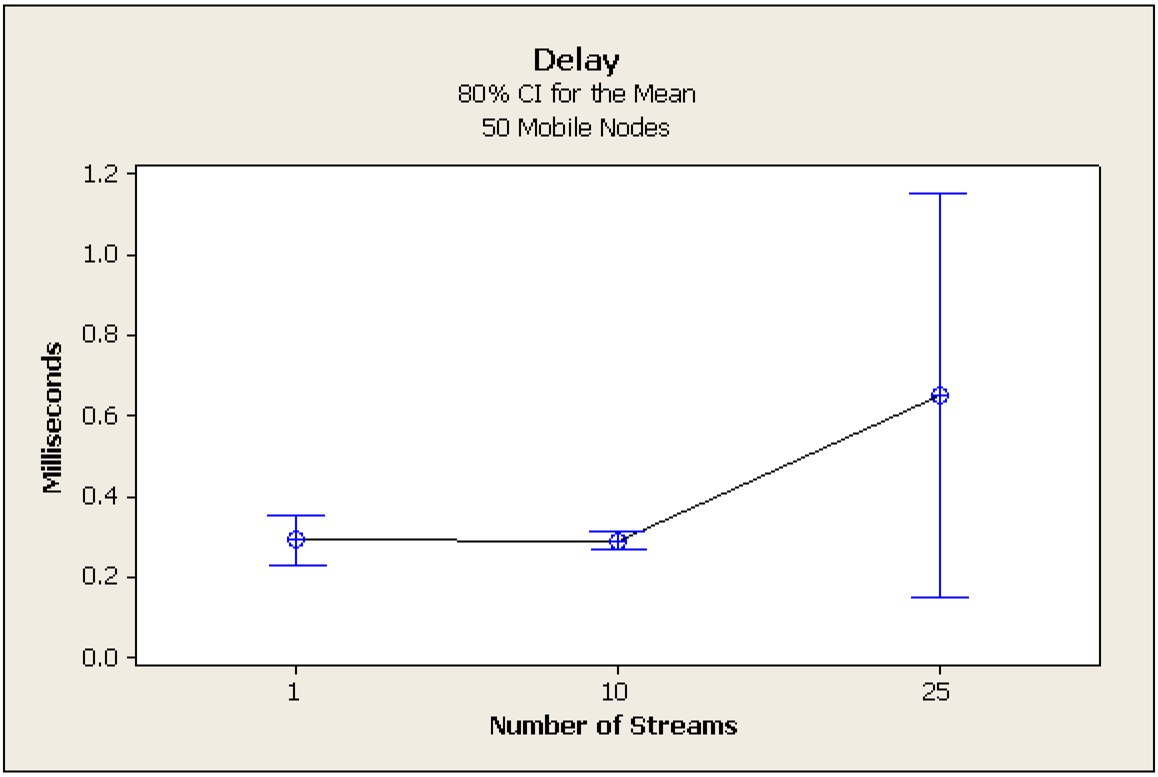


Figure C.6: Delay - 50 Mobile Nodes

C.1.4 1 Stream. Figure C.7 shows delay results for static scenarios with one stream. The means are not different since the probability of difference has a one-sided p-value of 0.347.

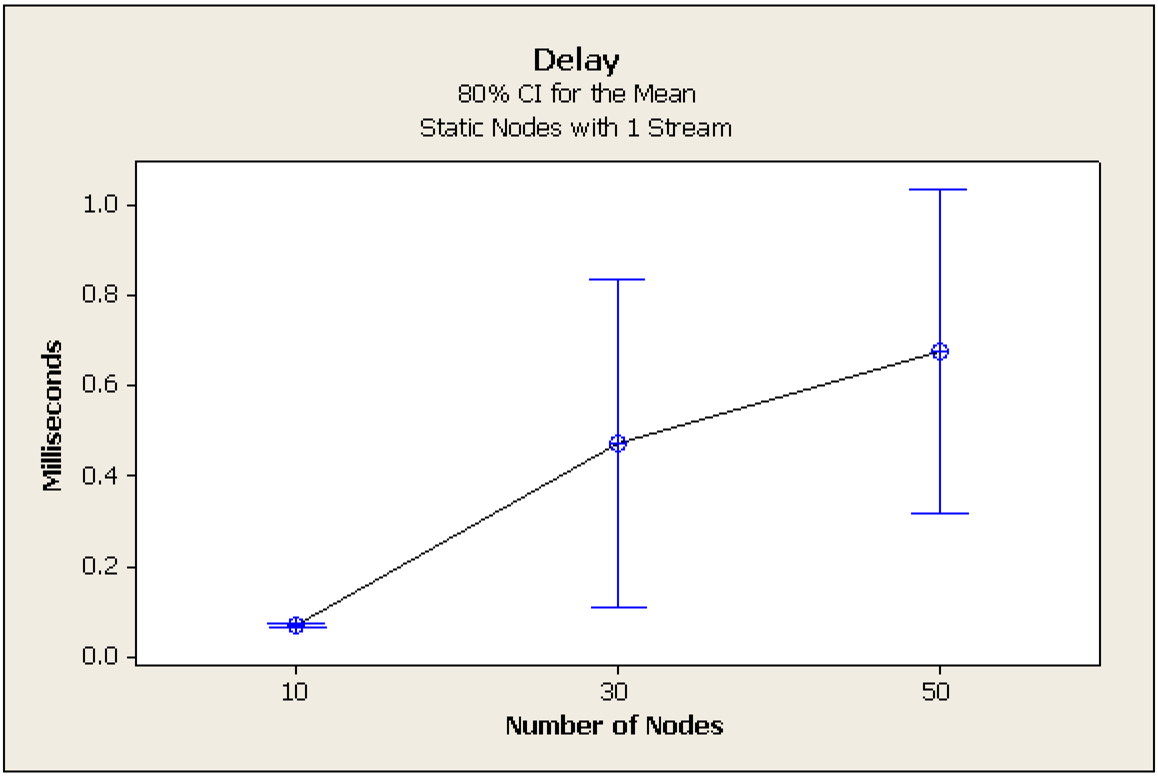


Figure C.7: Delay - 1 Stream (Static Nodes)

Figure C.8 shows delay results for mobile scenarios with one stream. The means are convincingly different with a probability of difference having a one-sided p-value of 0.006.

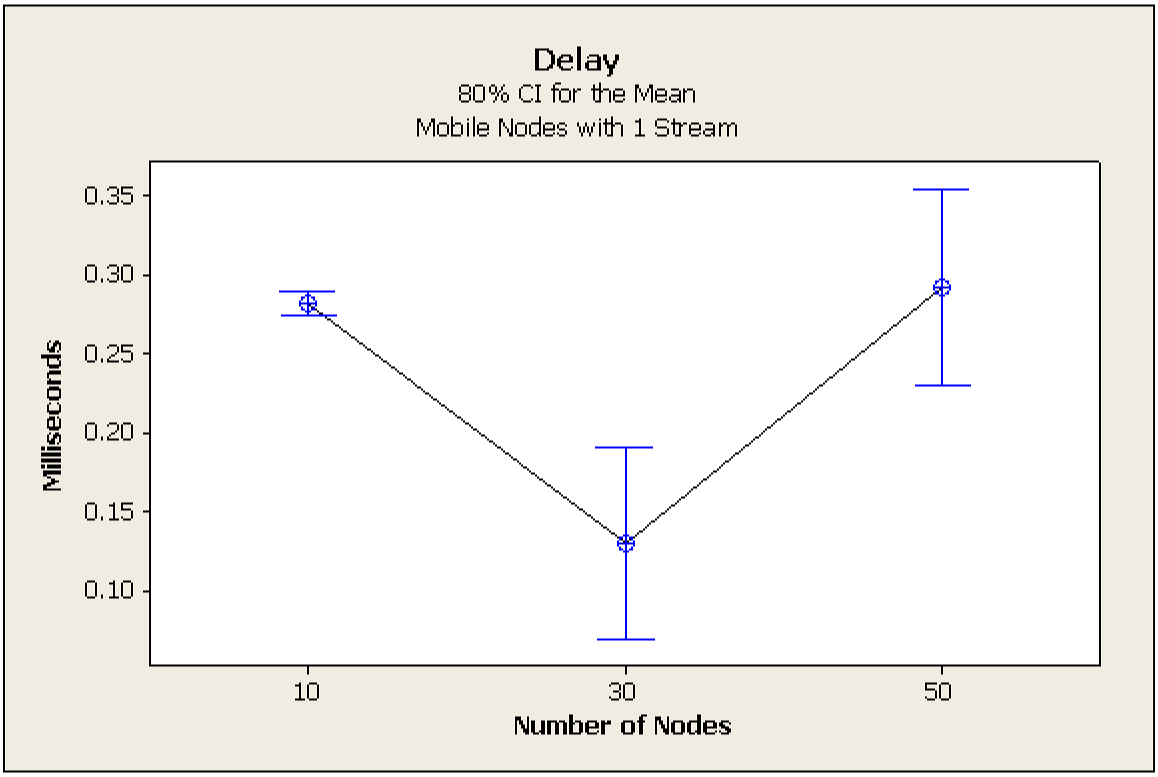


Figure C.8: Delay - 1 Stream (Mobile Nodes)

C.1.5 10 Streams. Figure C.9 shows delay results for static scenarios with 10 streams. The means are suggestively different with a probability of difference having a one-sided p-value of 0.235.

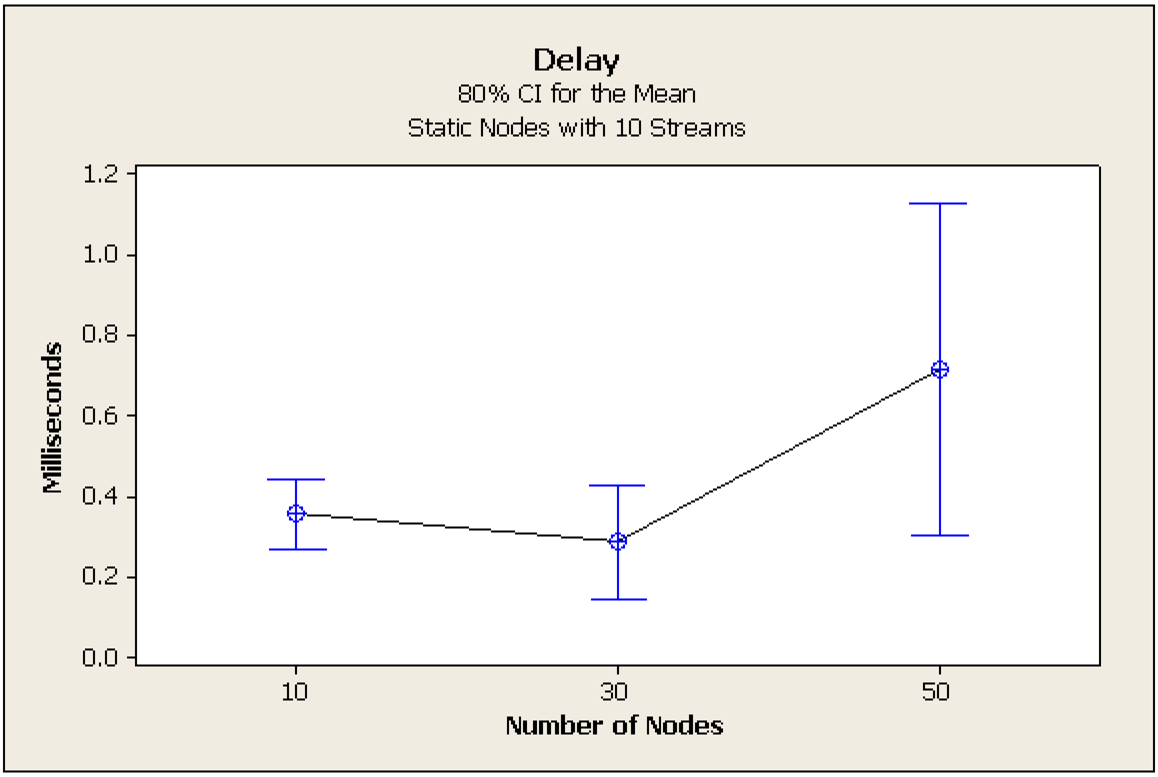


Figure C.9: Delay - 10 Streams (Static Nodes)

Figure C.10 shows delay results for mobile scenarios with 10 streams. The means are not different since the probability of difference has a one-sided p-value of 0.596.

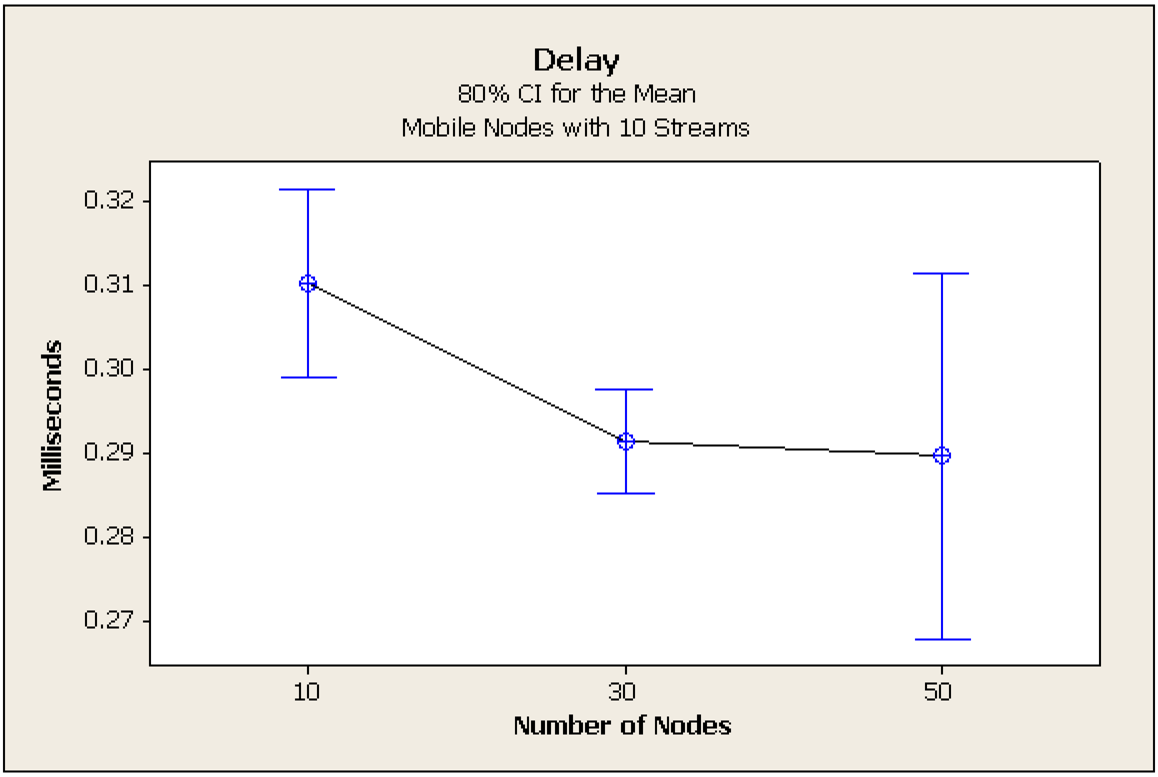


Figure C.10: Delay - 10 Streams (Mobile Nodes)

C.1.6 25 Streams. Figure C.11 shows delay results for static scenarios with 25 streams. The means are not different since the probability of difference has a one-sided p-value of 0.752.

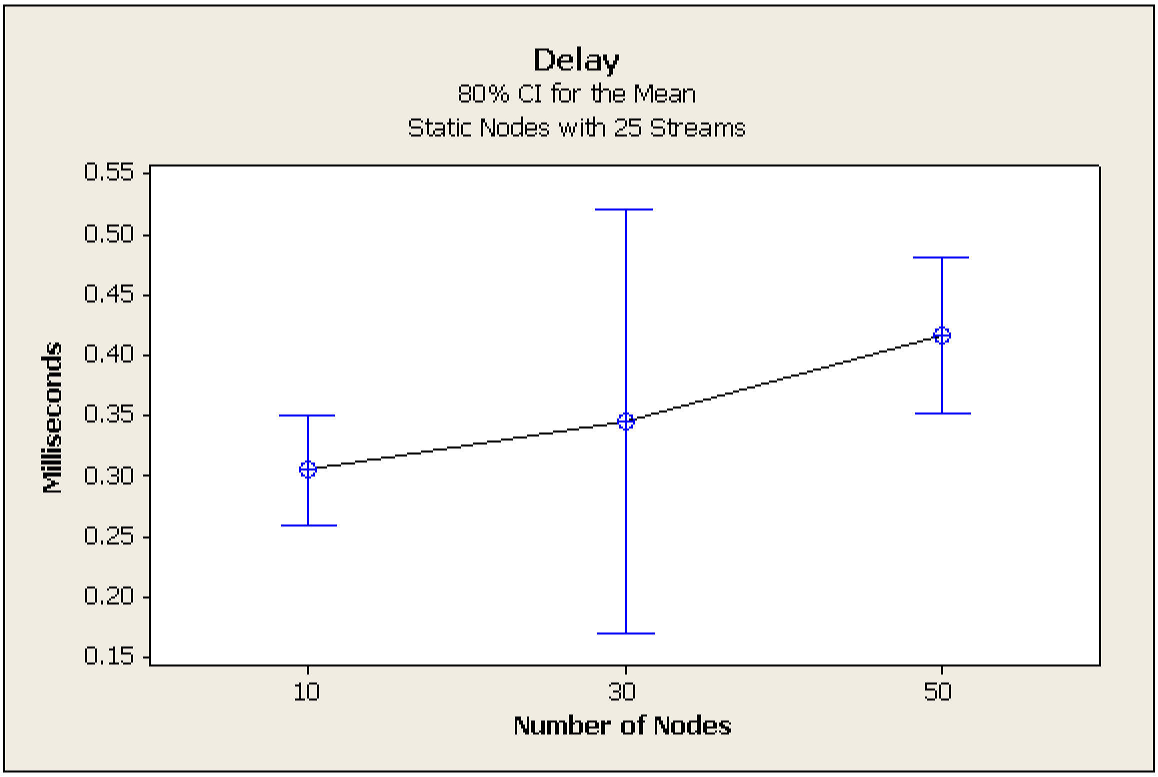


Figure C.11: Delay - 25 Streams (Static Nodes)

Figure C.12 shows delay results for mobile scenarios with 25 streams. The means are not different since the probability of difference has a one-sided p-value of 0.631.

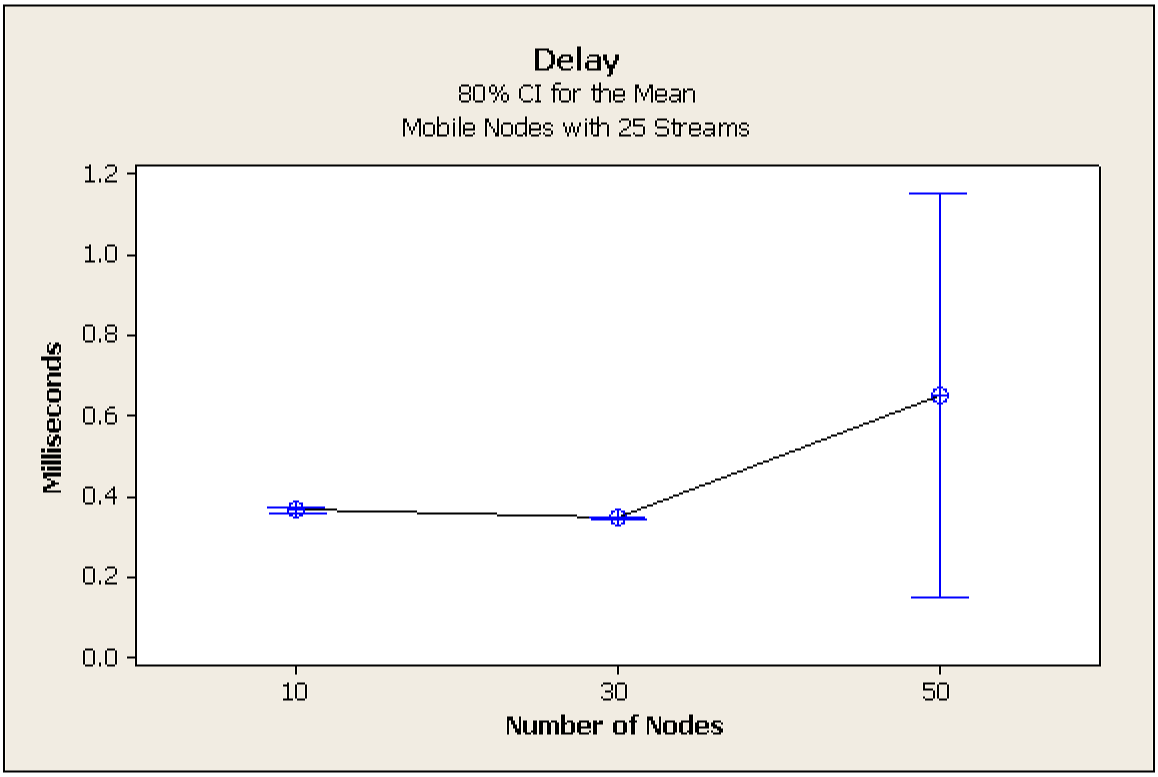


Figure C.12: Delay - 25 Streams (Mobile Nodes)

C.2 Packet Loss Analysis

C.2.1 10 Nodes. Figure C.13 shows packet loss results, in relation to the number of data streams, for the scenario with 10 static nodes. The means are not different since the probability of difference has a one-sided p-value of 0.479.

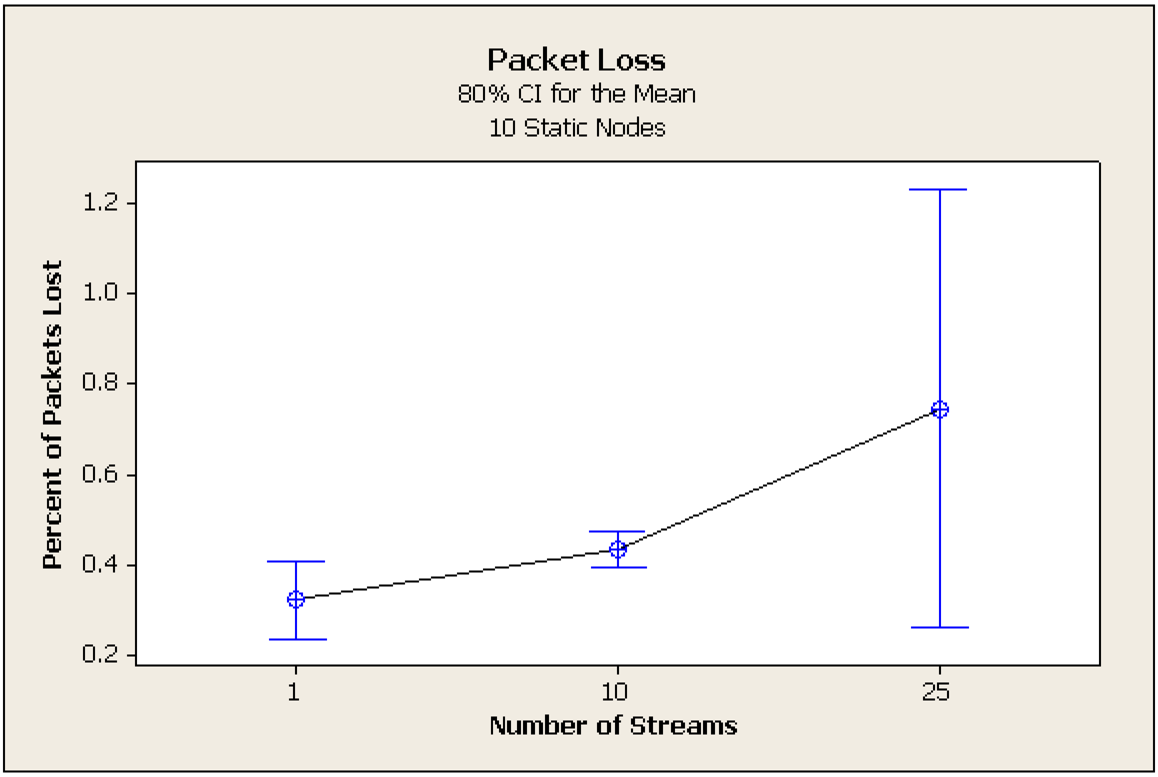


Figure C.13: Packet Loss - 10 Static Nodes

Figure C.14 shows packet loss results, in relation to the number of data streams, for the scenario with 10 mobile nodes. The means are moderately different with a probability of difference having a one-sided p-value of 0.153.

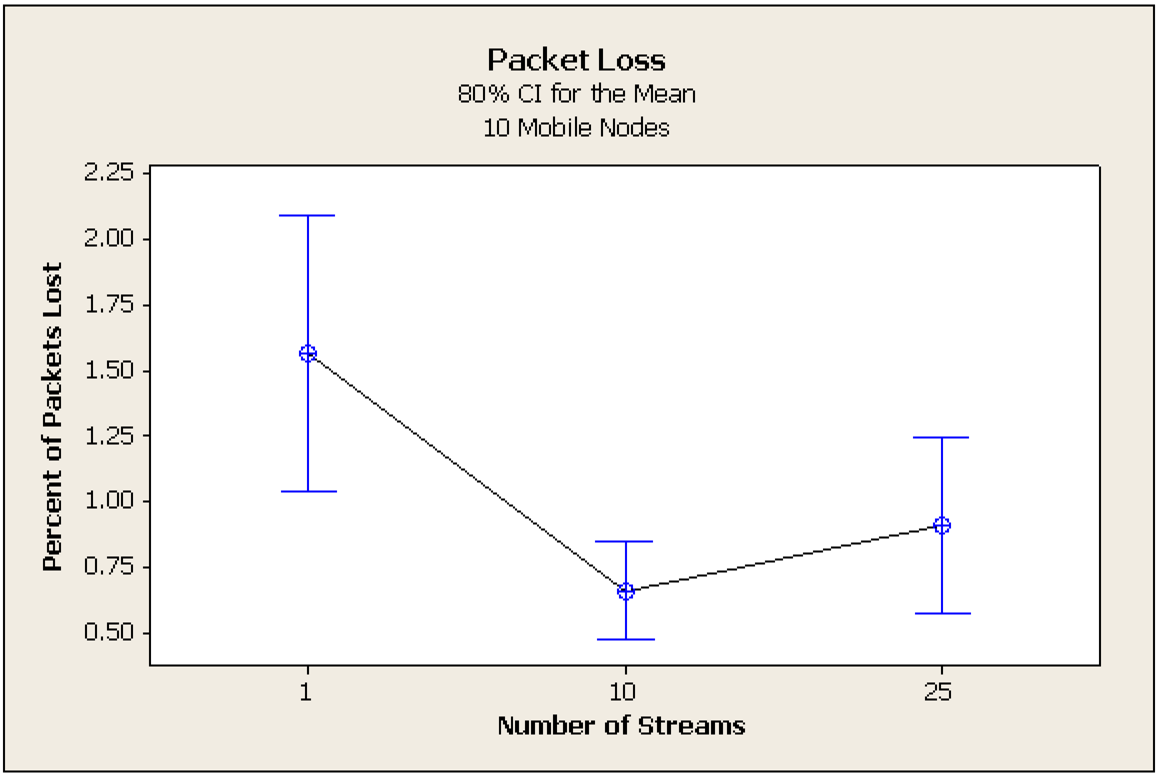


Figure C.14: Packet Loss - 10 Mobile Nodes

C.2.2 30 Nodes. Figure C.15 shows packet loss results, in relation to the number of data streams, for the scenario with 30 static nodes. The means are not different since the probability of difference has a one-sided p-value of 0.660.

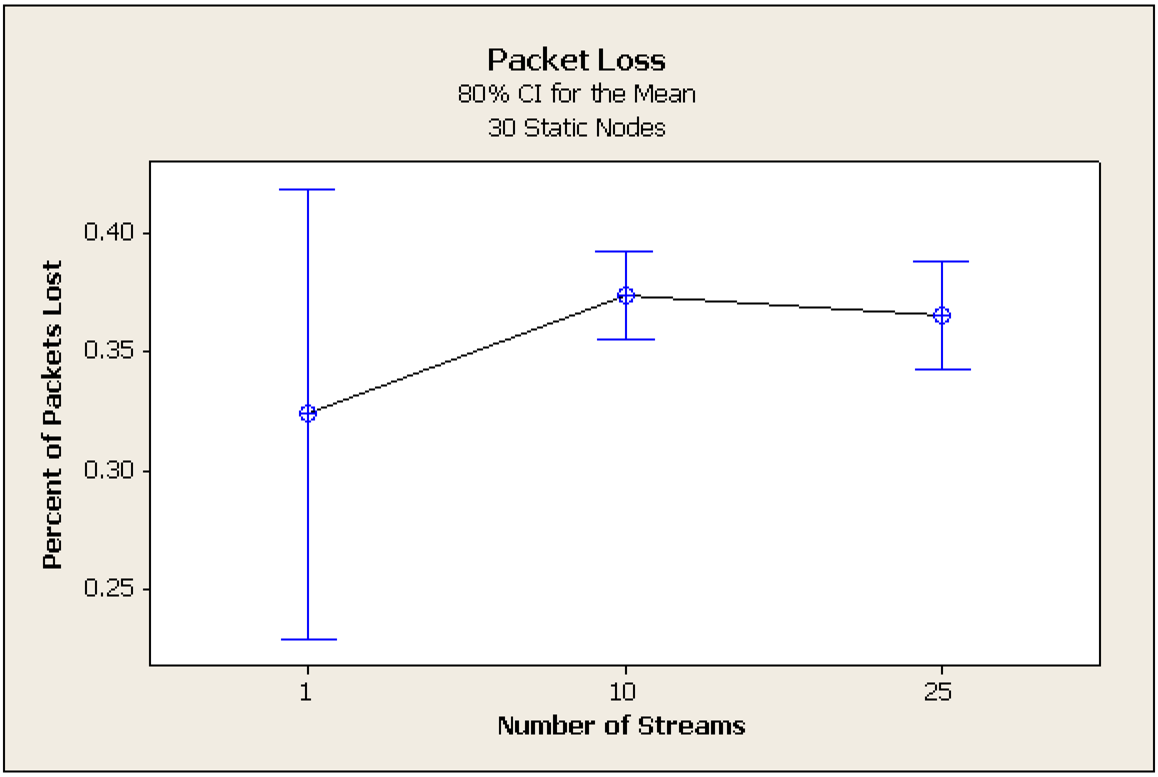


Figure C.15: Packet Loss - 30 Static Nodes

Figure C.16 shows packet loss results, in relation to the number of data streams, for the scenario with 30 mobile nodes. The means are not different since the probability of difference has a one-sided p-value of 0.653.

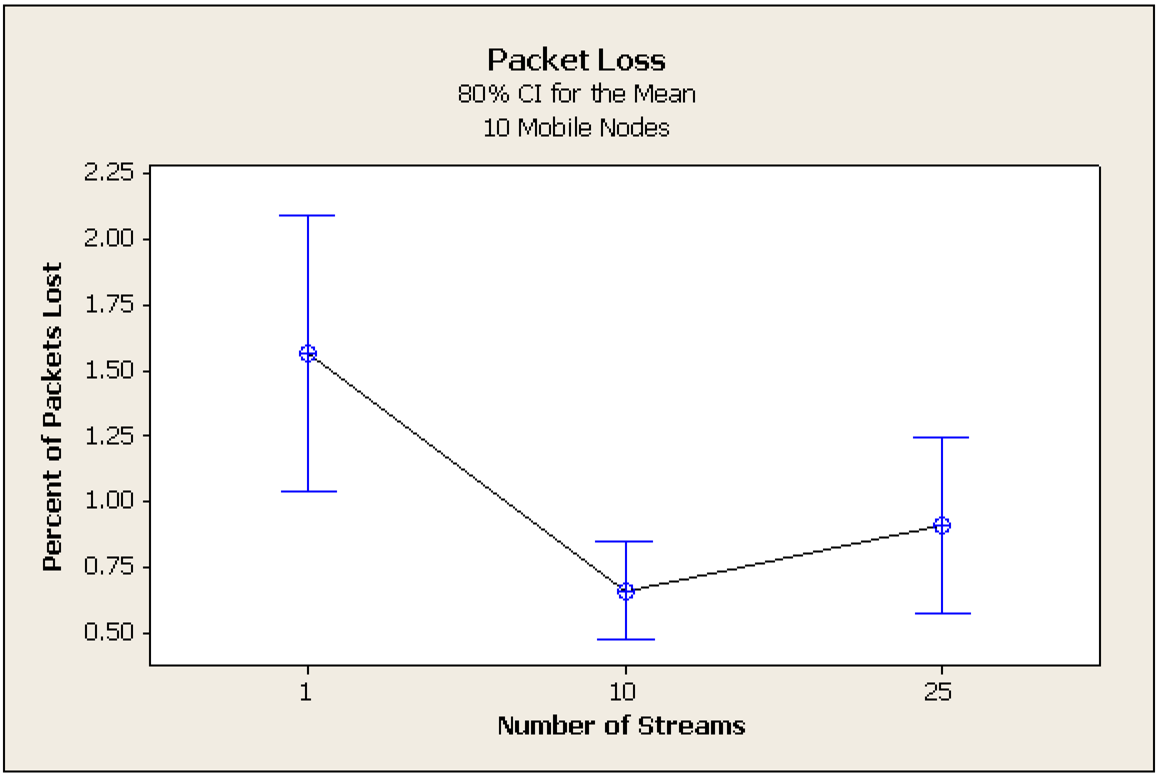


Figure C.16: Packet Loss - 30 Mobile Nodes

C.2.3 50 Nodes. Figure C.17 shows packet loss results, in relation to the number of data streams, for the scenario with 50 static nodes. The means are not different since the probability of difference has a one-sided p-value of 0.826.

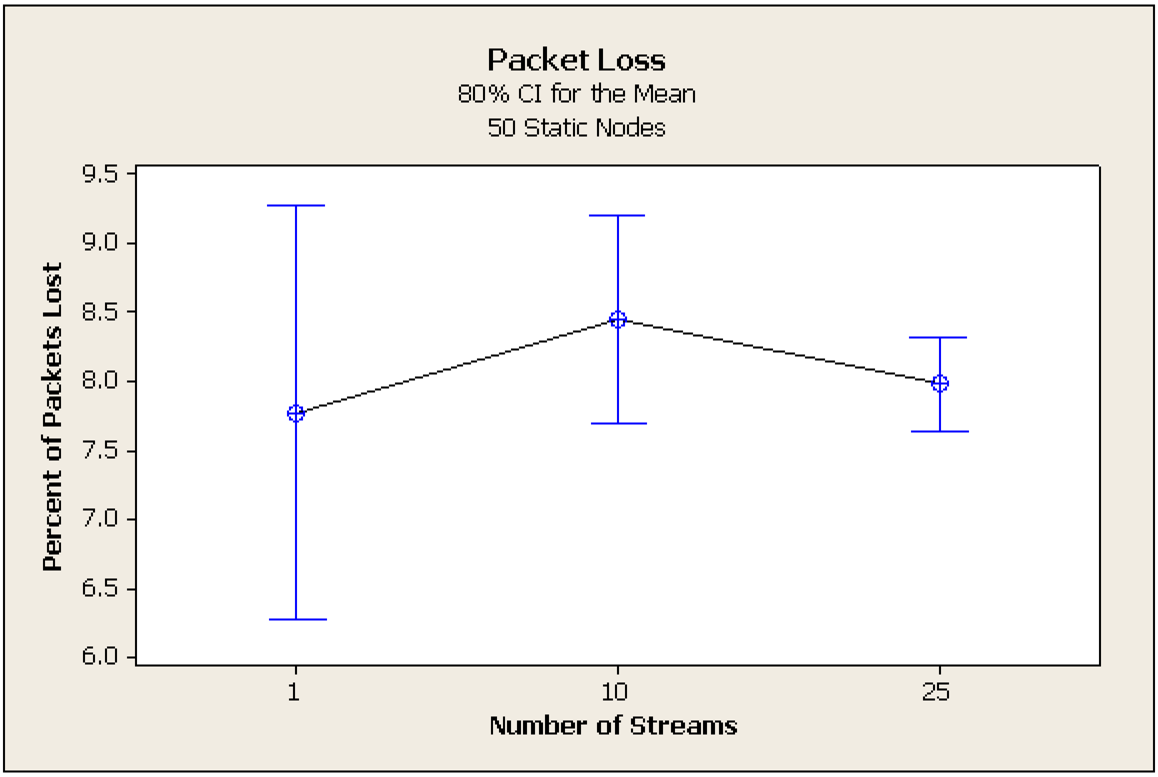


Figure C.17: Packet Loss - 50 Static Nodes

Figure C.18 show packet loss results, in relation to the number of data streams, for the scenario with 50 mobile nodes. The means are suggestively different with a probability of difference having a one-sided p-value of 0.219.

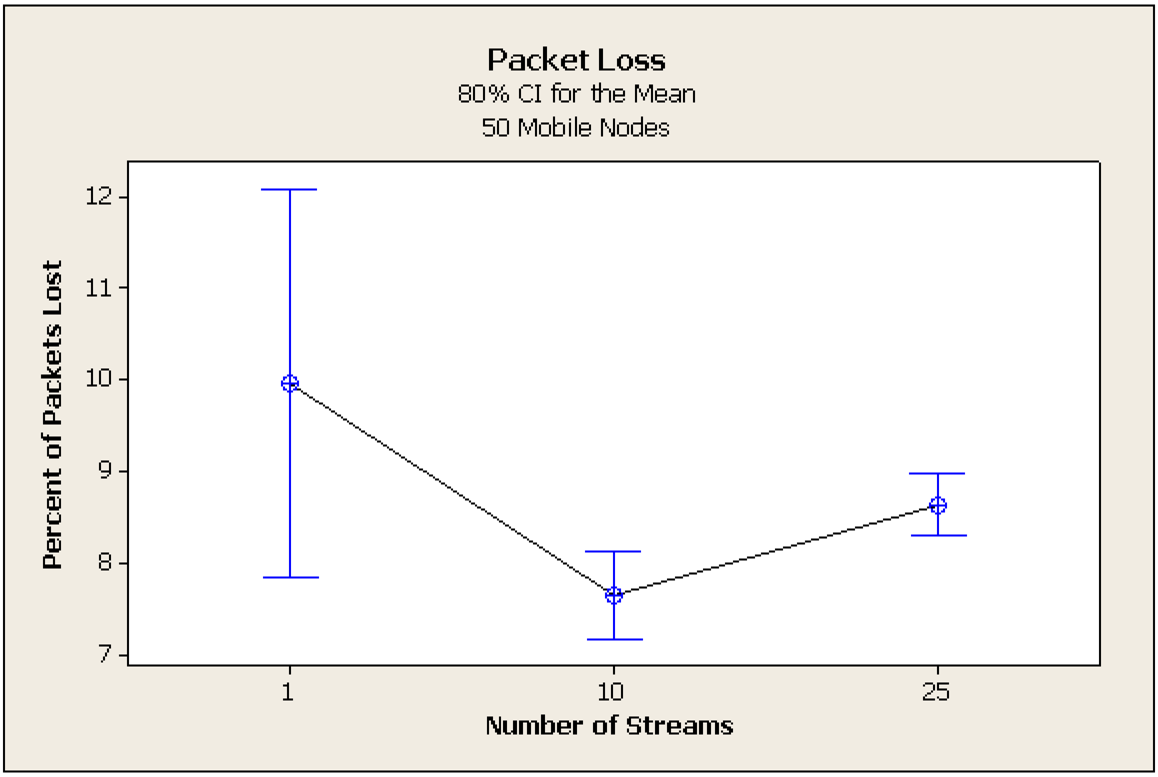


Figure C.18: Packet Loss - 50 Mobile Nodes

C.2.4 1 Stream. Figure C.19 shows packet loss results for static nodes with 1 stream. The means are not different between 10 and 30 nodes since the probability of difference has a one-sided p-value of 0.993.

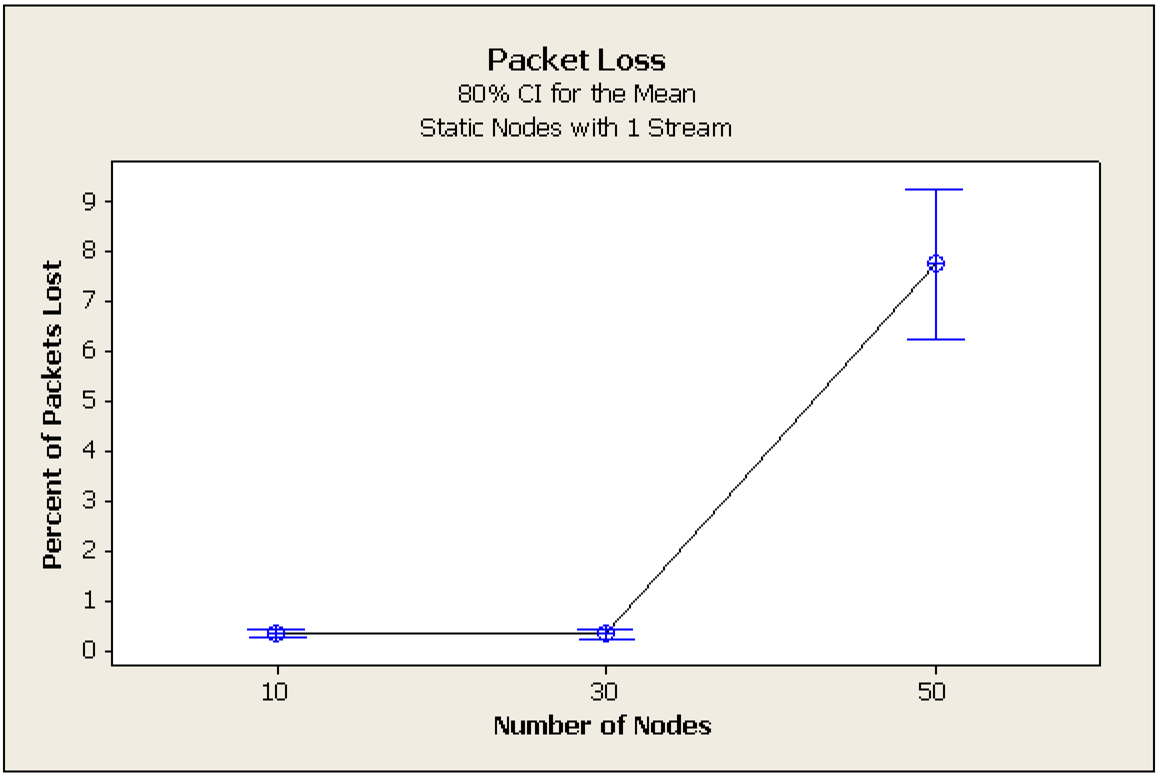


Figure C.19: Packet Loss - 1 Stream (Static Nodes)

Figure C.20 shows packet loss results for mobile nodes with 1 stream. The means are convincingly different between 10 and 30 nodes with a probability of difference having a one-sided p-value of 0.008.

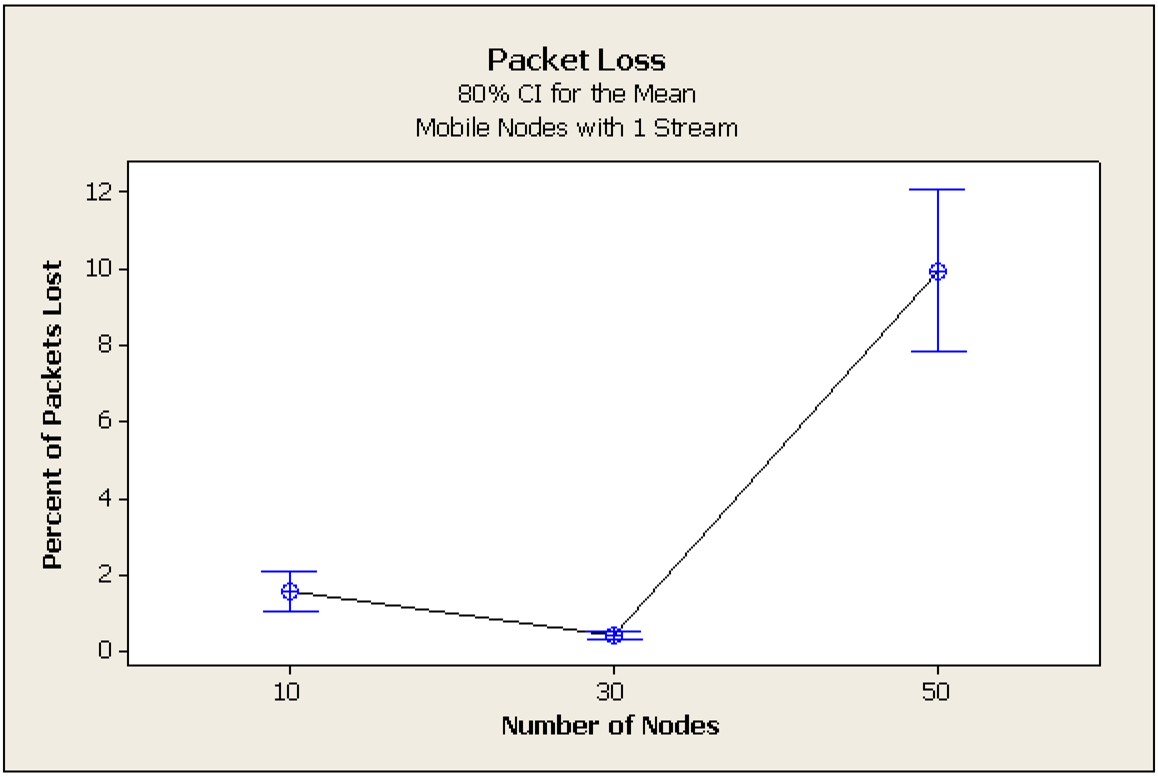


Figure C.20: Packet Loss - 1 Stream (Mobile Nodes)

C.2.5 10 Streams. Figure C.21 shows packet loss results for static nodes with 10 streams. The means are convincingly different between 10 and 30 nodes with a probability of difference having a one-sided p-value of 0.075.

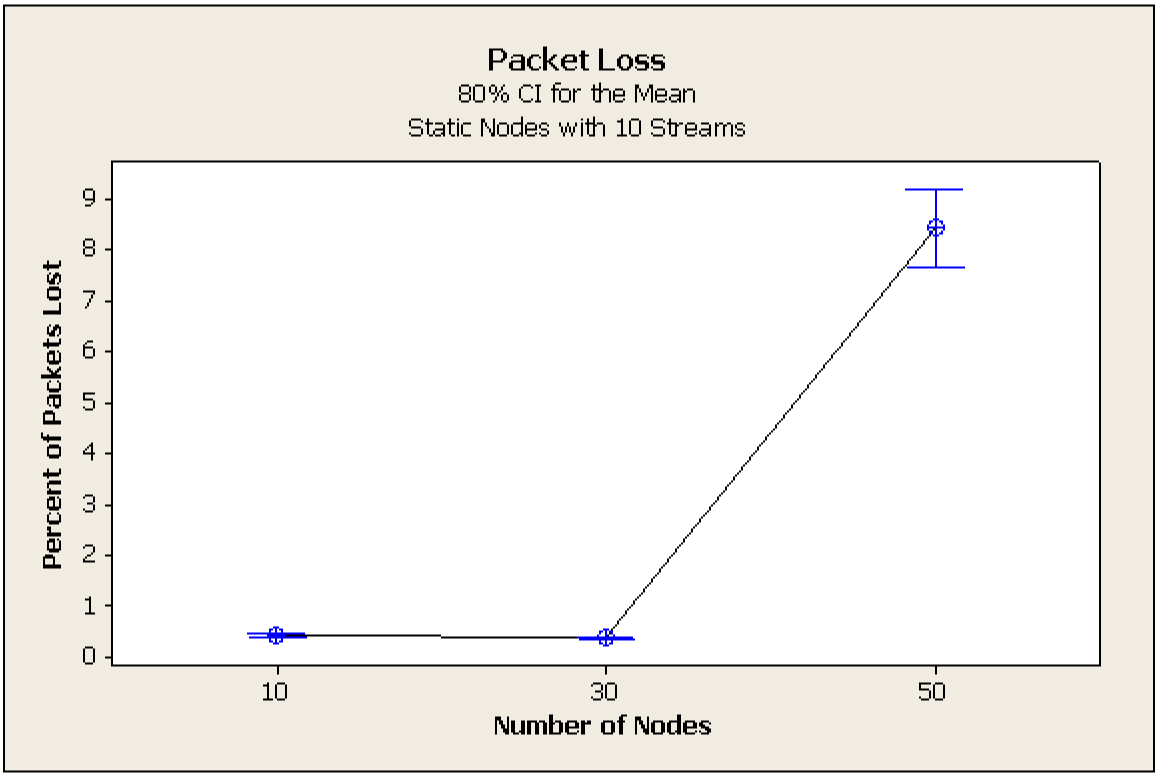


Figure C.21: Packet Loss - 10 Streams (Static Nodes)

Figure C.22 shows packet loss results for mobile nodes with 10 streams. The means are convincingly different between 10 and 30 nodes with a probability of difference having a one-sided p-value of 0.057.

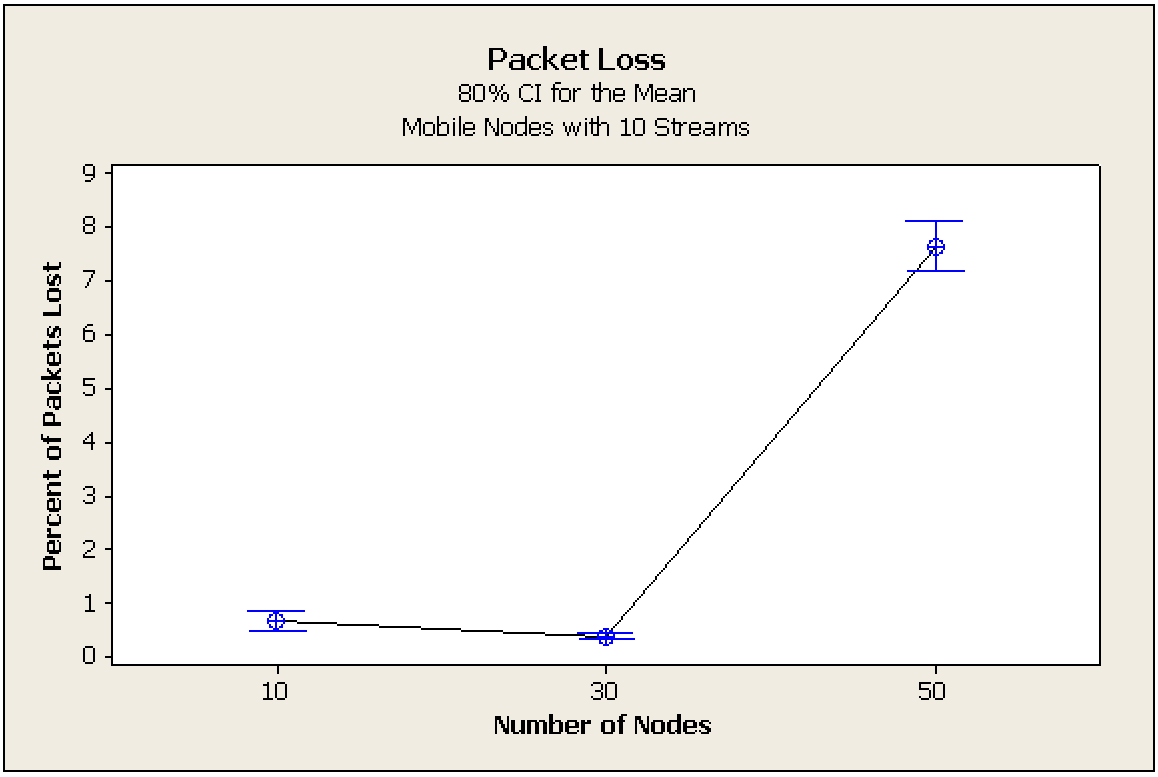


Figure C.22: Packet Loss - 10 Streams (Mobile Nodes)

C.2.6 25 Streams. Figure C.23 shows packet loss results for static nodes with 25 streams. The means are suggestively different between 10 and 30 nodes with a probability of difference having a one-sided p-value of 0.292.

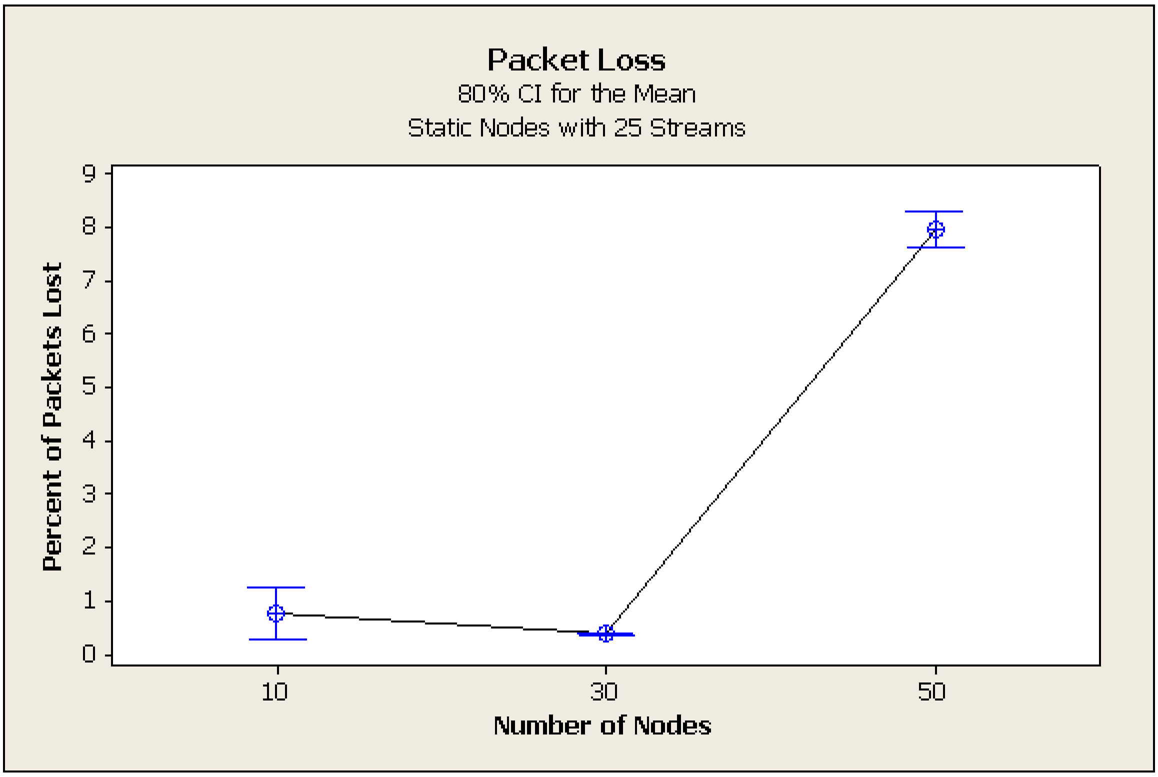


Figure C.23: Packet Loss - 25 Streams (Static Nodes)

Figure C.24 shows packet loss results for mobile nodes with 25 streams. The means are moderately different between 10 and 30 nodes with a probability of difference having a one-sided p-value of 0.131.

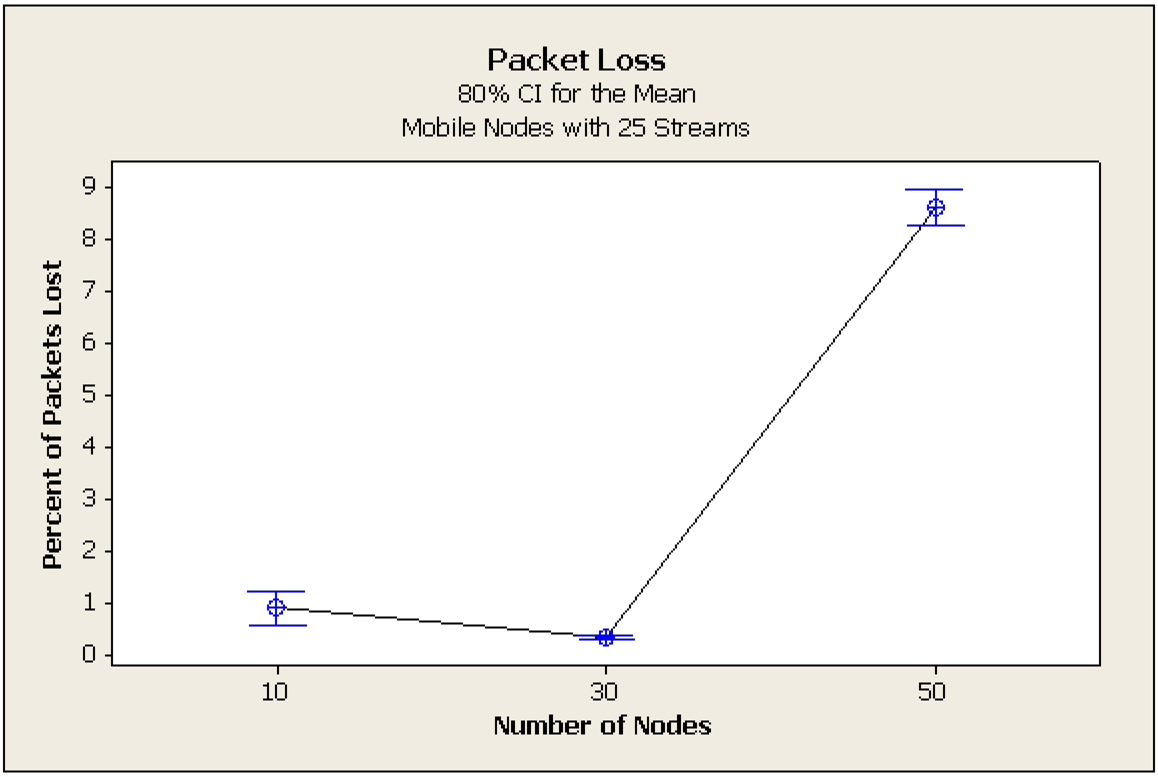


Figure C.24: Packet Loss - 25 Streams (Mobile Nodes)

C.3 Outliers

Outliers are data points that do not appear to belong with the rest of the values in the data set [ML08]. To proceed with data analysis, outliers must be identified and considered. Sources of outliers include:

- They can be due to data entry error.
- The data obtained is from a different population.
- They can be due to a systematic error.
- They can be caused by erroneous procedures.
- The theory in question is not valid for the data point.
- They are not due to any anomalous condition.

Outliers exist in this study and are shown in the following box plots - Figures C.25 and C.26. Box plots are helpful in identifying outliers in data since the outliers are shown by the star that falls outside the whiskers of the box plot.

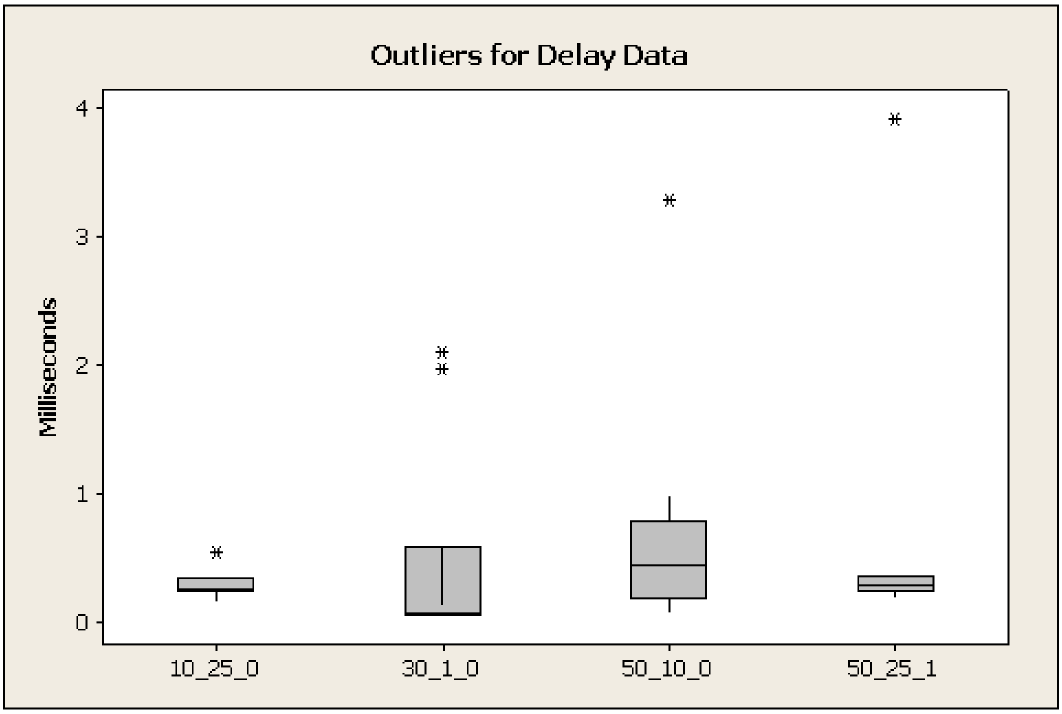


Figure C.25: Outliers in Delay Data

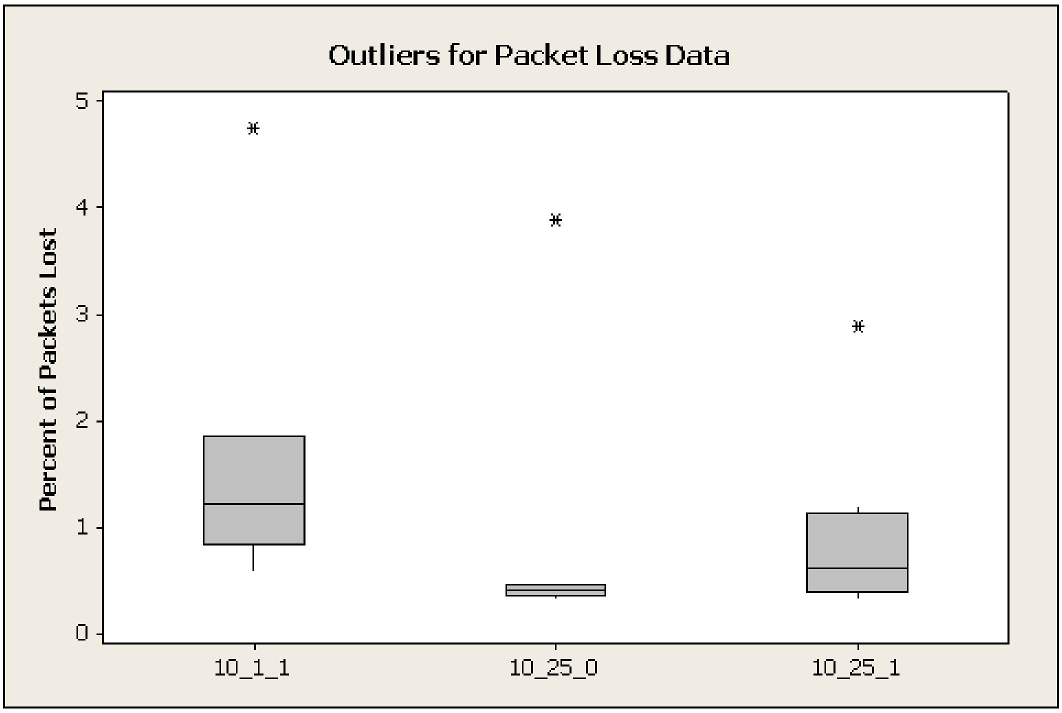


Figure C.26: Outliers in Packet Loss Data

Tables C.1 and C.2 run through the outlier identification criterion. These values are considered outliers since they do not appear to belong with the rest of the values in the data set.

Table C.1: Outlier Identification - Delay

	10_25_0	30_1_0	50_10_0	50_25_1
Data entry mistake	NO	NO	NO	NO
Obtained from different population	NO	NO	NO	NO
Systematic error	NO	NO	NO	NO
Erroneous procedures	NO	NO	NO	NO
Theory not valid	NO	NO	NO	NO
Not due to any anomalous condition	**YES**	**YES**	**YES**	**YES**

Table C.2: Outlier Identification - Packet Loss

	10_1_1	10_25_0	10_25_1
Data entry mistake	NO	NO	NO
Obtained from different population	NO	NO	NO
Systematic error	NO	NO	NO
Erroneous procedures	NO	NO	NO
Theory not valid	NO	NO	NO
Not due to any anomalous condition	**YES**	**YES**	**YES**

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14. ABSTRACT

This thesis investigates the performance of the Optimized Link State Routing (OLSR) protocol on Voice over Internet Protocol (VoIP) applications in Mobile Ad hoc Networks (MANETs). Representative VoIP traffic is submitted to a MANET and end-to-end delay and packet loss are observed. Node density, number of data streams and mobility are varied creating a full-factorial experimental design with 18 distinct scenarios. The MANET is simulated in OPNET and VoIP traffic is introduced using one source node to send traffic to random destinations throughout the network. Simulation results indicate delay is between 0.069 ms to 0.717 ms, which is significantly lower than the recommended 150 ms threshold for VoIP applications. Packet loss is between 0.32% and 9.97%, which is less than the 10% allowable packet loss for acceptable VoIP quality. Thus OLSR is a suitable routing protocol for MANETs running VoIP applications.

15. SUBJECT TERMS

Voice Communications, Communications Traffic, Internet, Wireless Computer Networks, Communications Networks, Routing, Simulation

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